NASA-CR- 54247

NASA

DEVELOPMENT OF ELECTRICAL SWITCHGEAR FOR SPACE NUCLEAR ELECTRICAL SYSTEMS

FINAL REPORT — PHASE I

For Period : July 16, 1963 Thru October 16, 1964

EDITED BY R. N. EDWARDS

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-2546 - PHASE I

SPACE POWER AND PROPULSION SECTION
MISSILE AND SPACE DIVISION
GENERAL ELECTRIC
CINCINNATI, OHIO 45215

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DEVELOPMENT OF ELECTRICAL SWITCHGEAR FOR SPACE NUCLEAR ELECTRICAL SYSTEMS CONTRACT NAS 3-2546 - PHASE I

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I. INTRODUCTION

The development of switchgear compatible with the nuclear and thermal environment of space power systems is of critical importance in system design. Such "hardened" components may be placed at the precise point in the vehicle where they will optimize protection and control. The limitations of system weight force the designer to limit radiation shielding and to operate the heat rejecting radiators at a high temperature. The switchgear technology developed under this contract (NAS 3-2546) has demonstrated operation well in excess of the target 1,000°F, with component designs which are appropriate to the 8,000 rad/min radiation flux.

The operational specifications of the devices investigated under this contract are tabulated below. It will be seen that experimental evaluation of the interruption technology was required only for the Main AC Circuit Breaker and DC Engine Contactor. The Main AC Circuit Breaker was studied only in the conceptual design detailed in Section IV.

DEVICE OPERATIONAL SPECIFICATIONS

Power System Requirements		
Main AC Breaker 600 A/3 Φ, 1,000 V, 2000~	Engine Contactor 10 A DC, 10,000 V	Main DC Breaker 10,000 A DC, 100 V
Phase I Technical Objectives		
Conceptual design, interrupt 1,800 A Pk, 1,500 V, 2000~	Conceptual design, interrupt 20 A DC, 10,000 V	Conceptual design Study only, no test
Experimental Test Results		
4,300 A Pk, 2,200 V, 2000~	21 A DC, 10,800 V	All at 600°C

The operating environmental requirements are compatible with use of the switchgear in the high temperature region of a vehicle quite close to a lightly shielded intermediate to fast spectrum reactor. These specifications are tabulated below, allowing peak dose rates of about ten times the average rate.

OPERATIONAL ENVIRONMENT

Heat Sink and Surrounding Ambient - $1{,}000^{\circ}F$				
Gamma Dose	- 10^{9} rad (carbon)	20,000 hours	- 8,000 rad/min	max.
Neutron Dose	- 10^{15} nvt (cm^{-2})	20,000 hours	- 10^{7} $nv(cm^{2}sec)^{-1}$	max.

Both the temperature and radiation specifications lead to a choice of ceramic insulators and unoriented metallic structures. The use of gas filling in the switches is limited to the very low voltage case by radiation induced ionization, and the hard vacuum switch approach is more favorable for both the high frequency and high voltage DC application.

These choices lead to a device which is suitable for even more rigorous environments than those specified, and the experimental program was carried out with contact tip temperatures of $1{,}200^{\circ}F$, exceeding the specification by 200 degrees. The limitations on the switches in the continuing program will be based on outgassing and pumping considerations rather than gross material damage.

The mechanical properties of the high temperature space power switchgear are not greatly different from those of their lower temperature counterparts. The launching stresses provide the basic limitations on the static and dynamic design in both cases. The use of torsional pivots in the high temperature actuator is, however, a novel feature imposed by the impracticality of high temperature lubrication of the moving parts. The launching stresses associated with the Saturn 1B vehicle (previously C1B) are representative of the mechanical requirements for the switchgear. As summarized below, these specifications are sufficiently stringent to demand very careful mechanical design, in which static and dynamic stability is inherent.

LAUNCHING ENVIRONMENT (Cold & Unenergized)

Shock	-	6	-	axis	35 "g"
Vibration	-	16	-	2,000 cps	6 - 19 "g"
Acoustic Noise	-	20	-	2,000 cps	148 db total
Acceleration	-	6	-	axis	7 "g"

The launching stresses were considered in the present study only in terms of the mechanical design limitations of the actuator concepts. No mechanical testing was included in the scope of this program.

In summary, the technical objectives of the space power switchgear program, first phase, were completed satisfactorily during this period. They were:-

1. To identify existing technology which was directly applicable to the requirements of space power switchgear.

2. To identify suitable contact materials and prepare electrode elements suitable for interruption tests.

3. To demonstrate interruption of high frequency AC currents in a high temperature switching device compatible with the space nuclear electrical system environment.

4. To demonstrate interruption of high voltage DC currents without restrike in a high temperature switching device as above.

5. To prepare detailed plans for the development of prototype space power switchgear which is compatible with the operational and environmental goals detailed above.

II THEORETICAL INVESTIGATION

The initial phase of the investigation was concerned with the selection of general types of switchgear devices and the special features of such selections that are determined by the application and particularly the special environment of the application. The cognizant switchgear, the general description of the application, and specific description of the environment were taken as stated in the contract. It is further recognized that the selection and design of devices to meet specifications of the contract should be such, (so far as practical), as to provide guidance for design and construction of similar devices of greater or lesser rating for similar or other applications in systems broadly similar to the one specified in the contract.

A. Interruption Techniques versus Environment

For each of the three devices of the contract, consideration was given to all the known and established techniques of conventional switchgear. These are principally air (including gas) breakers with either magnetic blowout or pneumatic blast arc extinguishers, oil immersed breakers and vacuum interrupters.

The conclusion of the investigation which resulted from comparison of the named classes of devices as used conventionally and consideration of the special needs and consequent modification for the contract application are as follows:

A.C. Breaker	Vacuum Interrupter
Engine Contactor	Vacuum Interrupter
Main D.C. Breaker	Gas (pressurized) Interrupter

The effective factors of the specified environment that were considered in evaluating each class of device were:

1. Radiation Exposure

The values taken into consideration were the total dosage stated in the contract and an exposure maximum rate, that might occur at any time, equal to 10 times the average of the total dosage acquired over 20,000 hours. Pertinent areas of effect, for the initial examination, are: arc interruption, material physical and chemical degradation and contribution to temperature rise.

The effects of this radiation exposure on the materials and gases that have potential application in switchgear was the subject of a study and literature review conducted by the "Radiation Effects Operation" of General Electric Company at Syracuse, N.Y. Appendix A is a copy of the report titled, "Evaluation of the Effects of Radiation on High Temperature Electrical Switchgear for Space Nuclear Electrical Systems." A summary of the areas investigated in the study yields the following conclusions:

a. Ionization rates were computed for both neutrons and gamma radiation on the various gases at respective ambient conditions of temperature and pressure. The increased ionization due to radiation incident on the outer envelope is included. Computations indicate that electron emission from the outer envelope contributes the highest ionization rate in the switchgear.

b. Limited information is available on gas liberation from materials due to irradiation - essentially all data are presented on a qualitative basis rather than quantitative.

c. Nuclear heating within the various materials in the switchgear appear to present minimum heat addition to the ambient temperature environment of 1000° - 1300°F.

d. Total radiation-dosage of 10^{15} neutrons/cm^2 will present little problem to the structural integrity of materials. Essentially, threshold levels for detecting initial structural defects will not be reached.

e. In some magnetic materials, threshold changes are reached at 10^{15} neutrons/cm^2 total radiation dosage. However, the majority of magnetic materials do not exhibit nuclear effects in their physical properties before 10^{16}-10^{17} neutrons/cm^2. Hard alloy type magnetic materials are the more radiation resistant.

f. Seal integrity is difficult to ascertain due to the long mission requirements of 20,000 hours together with ambient effects of pressure and elevated temperature. Utilization of active type seals would provide increased stability in the combined radiation-temperature pressure environment than the metallized types.

g. Sublimation of materials is primarily a temperature-vacuum effect rather than radiation. Loss of materials may result in mechanical defects that may limit material integrity for specific applications. Increased ionization due to radiation incident on vaporized material will occur, the extent of which has not been evaluated.

Based on the conclusions contained in the report, the effects of the radiation on the interruption mechanism of each class of switchgear was analyzed.

In examining gas immersed switches for the AC Circuit Breaker and the DC Engine Contactor, one would consider air or nitrogen in the range of 1/2 to 2 atmospheres as a conventional material. Although there would be problems of strength, stability, and effectiveness of arc chutes, special materials for blowout insulation, if used, and of effectiveness of gas blast components.

At the "red hot" temperature it is sufficient to determine that the radiation exposure would prevent normal extinction on both devices. Appendix A, page 9 shows that, due to radiation, the ion formation in nitrogen (or air) at 1/2 to 2 atmospheres would be about 5.25 to 17.6 x 10^{10} ion pairs per cc per second. If it is assumed that ion density stability, near a normal current zero in the interval when recovery voltage is low, is achieved by balance between this rate of formation and the rate of recombination in the gas between the contacts or in the arcing chamber, the value of stable ion density is determined by the formula

$$n = \sqrt{\frac{q}{a}}$$

where n is the stable ion-pair density in pairs per cc, q is the rate of ion-pair formation in pairs per cc per second, and a is a recombination coefficient.[1] This yields values of about 2 to 3 x 10^8 ion pairs per cc. This density is comparable to the density in a low pressure glow discharge.[2] It is sufficient to cause re-ignition in the AC Circuit Breaker and re-strike in the DC Contactor. If hydrogen or sulfur hexafluoride were used instead of nitrogen or air, the ion density would be up to 10 times greater, depending on the pressure used. This alone tends to prohibit the use of gas at atmospheric or high pressure in the high voltage (1 KV and 10 KV) switchgear.

In respect to the DC Circuit Breaker, 100 volts and 10,000 amperes, subject to study of a conceptual design, the possible stable ion density of 10^9 ion pairs/cc is not presently taken to rule out this form of switch because of the low voltage. It is known that the forms of switchgear to be proposed for the higher voltage are not adaptable to this service. The extraordinary arc suppression characteristics[3] of high pressure hydrogen appear useful in a DC switch of the referenced current and voltages.

In examining the vacuum interrupter for the AC Circuit Breaker and the DC Engine Contactor one would determine whether or not radiation exposure poses an obstacle similar to the effect in the gas immersed interrupter. In this case, the calculations for rate of ion formation due to radiation, as presented in Appendix A, might run as high as 967 to 13,900 ion pairs/cc/sec. depending on the residual gas composition and pressure. These figures correspond to a pressure of 10^{-4} Torr in hydrogen and air, respectively. The switches would be built with initial pressure at least down to 10^{-6} Torr at room temperature, and the residual gas preferably would be hydrogen, which is the more favorable for minimizing ion formation due to radiation. However, lacking firm data as to the operating pressure at the high ambient temperature, the higher values quoted above for ion formation, are used.

For a vacuum device, the stable ion density is determined by the balance of rate of formation due to radiation and rate of loss due to diffusion. This is not the same as loss due to volume recombination used in the analysis of the gas immersed device because volume recombination as a mode is suppressed by the fact of the mean free length of space between gas particles being greater than the dimensions of the envelope. Calculation of the equilibrium ion density where the formation is by radiation and the loss is by diffusion is given by the equations:

$$n = \frac{q}{2D}\left(xd - x^2 + \frac{4Ld}{3}\right) \qquad \text{ref. } \underline{4}$$

and

$$D = \frac{LC}{3} \qquad \text{" "}$$

where

n = ion density in pairs/cc at x

q = rate of ion formation due to radiation in ion pairs/cc/sec.

D = diffusion constant

L = mean free path between ions in cm

C = ion average velocity in cm/sec.

x = distance from one electrode to point at which density n is taken in cm

d = separation of electrodes in cm

In this analysis the maximum density is calculated. This obviously is when $x = \frac{d}{2}$. C may be calculated from the well-known formula of the kinetic theory of gases[5]

$$C = 1.868 \times 10^{-8} \sqrt{\frac{T}{m}}$$

where

m is the mass of a single ion in grams

T is the temperature of the ion in deg. K

L is calculated for hydrogen and air based on the values at NTP[6] and increased by the ratio of one atmosphere pressure to pressure of 10^{-4} Torr. This is a conservative estimate which assumes the pressure in the vacuum switch would be as high as 10^{-4} at normal temperature.

T is taken as 2000°K to 5000°K. These are respectively the lowest temperature of the arc footpoints on the contacts, and of the plasma which are the possible sources of ions.

Combining the equations quoted yields:

$$n = q\sqrt{\frac{m}{T}} \left[2d + \frac{3}{2L}(xd - x^2)\right] + x\,(1.868 \times 10^{-8})$$

or

$$n_{max} = q\sqrt{\frac{m}{T}} \left[2d + \frac{3d^2}{8L}\right] \div (1.868 \times 10^{-8})$$

For a separation d . 1 cm

$$n_{max} = q\sqrt{\frac{m}{T}}\left[2 + \frac{3}{8L}\right] \div (1.868 \times 10^{-8})$$

Since L for hydrogen and air, at 10^{-4} mm Hg pressure has values of 136 and 68, respectively, it is seen that the term inside the bracket is approximately 2, and insensitive to considerable variation in the value of L. The maximum ion pair density, for the conditions quoted is then from 0.2 to 13 ion pairs/cc. It is the considered opinion of experienced associates working in the fields of plasma and gaseous conduction phenomena that this density will not contribute significantly to a decrease of the value of voltage required to break down the dielectric space between contacts.

The oil immersed switchgear were not studied in detail with regard to the effects of radiation exposure since the high ambient temperature eliminates this class. The details are given in the following paragraphs.

2. High Temperature

The ambient and heat sink temperature was stated to be 1000°F (538°C). This would lead to a temperature at contacts and other parts of 688°C if a tentative allowance of 100°C steady state rise and 50°C additional short time rise were made. This, literally, is a "red hot" temperature. Pertinent areas of effect, for the initial examination are: arc interruption, contact welding, metal sublimation, material physical and chemical degradation.

The oil immersed switchgear of the classes considered is most readily eliminated from further consideration. Temperature and radiation effects are both much more harmful to this type of interrupter than to others. Deterioration of the oil and the contacts is severe even under conventional conditions, and there is no clear advantage so far as weight, mechanical balance, seal and support are concerned. With respect to temperature, it may be noted that conventional circuit breaker oil has a "flash point" specification of 135°C and a "burn point" specification of 148°C.[7] Special insulating oils, possibly suitable for switchgears, have a "burn point" specification as high as 193°C.[8] All mineral oils crack, polymerize and depolymerize at temperatures in the range of the proposed switchgear. All mineral oils are sensitive to radiation, and likewise degrade in it. While it is conceivable some liquid less chemically complex than mineral oil might be used, there is no substantial background experience for such in switchgear technology. It appears that it would be much more effective to examine the other classes of switchgear.

3. Mechanical Environment

This was specified as the launch conditions of a C1B vehicle and may be represented as follows:

Shock 35G

Acceleration 7G

Vibration	Scan	Resonance Point
16-100 cps	6G	3G
100-180 cps	0.0118" P/P	0.0059 P/P
180-2000 cps	19G	9.5G

All of the above to be applied in each direction through three major axes.

Acoustic noise - 148 db - 200 cycle peak referred to 0.002 microbar.

The mechanical environment was considered to affect all classes of switchgear in a similar manner and was not a factor in selecting the classes of switchgear for each contract device. The mechanical environment is effective, principally in the mechanical design, with respect to simplicity, balance of inertial forces and strength of supports and seals.

The foregoing is the basis of the selection of switchgear types as quoted at the beginning of this section of the report. The radiation exposure was the major factor in influencing the selections. The radiation study indicated the vacuum interrupter for the AC Circuit Breaker and the DC Engine Contactor. It also showed that a pressurized gas interrupter was suitable for the Main DC Breaker. The mechanical environment was not a factor in the selections. The high temperature, however, eliminated the oil immersed class and a further discussion of the effects of the high temperature on the pressurized gas interrupter is contained in the report under the conceptual design of this device. A more detailed examination of the effects of the high temperature on the performance of vacuum interrupters follows.

B. Vacuum Interrupters

The technology developed for commercial vacuum interrupters is to be applied and extended, where necessary, to the application conditions and launch and space environment of the contract AC Circuit Breaker and DC Engine Contactor. The areas of study reported herein pertain principally to the special effects of radiation and temperature. The radiation effects study reported in Appendix A has been used so far to help establish the choice of vacuum interrupters as reported in the foregoing discussion and will further be used to help establish in detail the material and processing of the vacuum envelopes and actuator. The effects of the high temperature of the environment has been studied and is reported herewith with respect to the contacts of the vacuum interrupters.

1. Contact Requirements

For vacuum switch interrupters the contact material must be compatible with requirements to -

a. Interrupt AC over the entire rated current range by the rapid condensation of metal vapor at a current zero.

b. On AC preferably maintain an arc on current declining toward the current zero down to a low value of current such as a few (less than four) amperes.[9,10] This avoids or reduces a current "chop" and thereby prevents high voltage surges. It is recognized that in the present study the interrupters are applied in a self-contained system, and therefore if it appears to be in the interest of a best balanced system it may be desirable to accept a degree of "chop" and some external or other control of voltage surge.

c. Interrupt DC by the starvation of metal vapor generation at the highest rated current interruption. This inherently is a "chop". The amount of voltage surge is a combined function of the "chop" current and the circuit surge impedance. In this application it is expected that the surge impedance will be such as to prevent excessive voltage surge.

d. Close in on current, carry normal (or less) current continuously and carry short pulses of high current without welding sufficiently to prevent normal opening and closing of the contacts. It is true, from a practical view, that the welding of contacts, defined by the tensile force necessary to part the contacts, cannot be reduced to exactly zero. In all practical interrupters it is reasonable to provide a certain amount of weld-breaking force in the actuator. For example, in the interrupters of this study it might be a few pounds. Some welds may be brittle. This means that they fracture on tensile pull without much elongation. This in turn means that even though the force to break the weld can be high, not much mechanical energy is required to break the weld and the high force over a very short distance can often be provided conveniently by an impact mechanism in the actuator. In conventional interrupters often a mechanical leverage is provided to help fracture the weld. In the present study it was anticipated that contact welding would be controlled principally by -

- Choice of metals that produce weak welds
- Choice of metals that produce brittle welds
- A designated minimum of steady opening force
- An impact mechanism
- Control of closing speed and mass to tend to minimize weld forming energy

2. <u>Contact Welding</u>

A discussion of some factors involved in the choice of contact metals follows:

Welding or sticking of electrical contacts can occur in switchgear unless specific steps are taken to prevent it. The conditions present in commercial vacuum interrupters, and even more so those created by the environment specified for the switchgear of this study promote contact welding unless the contacts and actuation are specifically controlled to prevent welding. Commercial vacuum interrupters have been so controlled. This discussion examines the means required to render similar control for the interrupters designed for the specified space environment.

For the purpose of this examination the modes of welding or sticking of contacts are classified under four headings. These are arbitrary classifications for this discussion. It should be recognized that when the mechanisms of bonding are examined on an atomic scale there are some processes that are common to two or more of the modes named, and in general all the mechanisms tend to merge into an interrelated family of processes.

a. Melting of the contact metals with consequent freezing and recrystallization across portions of the original interface. - This mode can occur in conventional and special devices when the contacts close on high current, especially with bounce, and on passage of high current pulses when already closed. Speed of closure, mass, spring constant and damping of the contact mechanism, contact force, electrical resistivity, elasticity, hardness, yield strength, elongation characteristic and structure (such as homogenous metal or impregnated matrix) of the contact metal are characteristics that are controlled to minimize or reduce this effect.

A variation of this mode, also related to a mode discussed below is "sintering with a liquid phase".[11] Due to the presence of the liquid phase this mode may be controlled much as described above.

b. Quick diffusion of the solid contact metals across the interface. - This sometimes is called welding by atomic attraction or cold welding or cohesion.[10] It occurs when pure, clean molecules or crystals of metal across the original interface come into intimate contact with each other. The bonding takes place instantly or quickly, which in this context will be defined to be in the range of milliseconds. Normally this does not occur in air-break or other conventional interrupters because the oxidation or other contamination of the contact faces prevents the essential intimate contact of pure metal to pure metal. It can occur in vacuum switches not designed to avoid it. The hardness, crystal and lattice structure, elongation characteristics of the metal, and contact force are avenues for control of the strength of welds of this kind.[9,12,13,14] In this mode of welding it is conceived that the presence of any gas film will reduce the tendency to weld. In the mode discussed under heading (d) below, it is conceived that the presence of a critical amount of gas on the surface of the metal may induce some sticking. Therefore, in the tests for both of these the amount of sorbed gas should be controlled. The tests can be conducted at one pressure, say 10^{-6} Torr and time controlled to produce film formation such as would occur at another pressure, say in the range of 10^{-6} to 10^{-13} Torr.

It should be especially noted that mutually insoluble metals can be made to cohere, probably by process (b). Silver or lead on steel or iron are examples. This emphasizes the fact that there is no easy, simple rule by which to choose contact metals, even for anti-welding alone, not to mention the other necessary conditions named.

c. Sintering. - This name is drawn from the commercial process in which metal powders are bonded by the application of heat below the melting point for times normally in the range of a few hours. On an atomic scale it is a complex process involving metal transport by at least three or four mechanisms.[15,16] These mechanisms are forms of diffusion. It is well known that the over-all process takes place at increasing speed as the temperature is increased and that there is a sharp increase in speed, sufficient to produce strong bonds in a few hours or less, at the "Tamman temperature". This temperature is a value in a narrow band near one-half the melting point of the metal involved, on an absolute scale. The actual value, for a variety of substances, is usually stated to be between 37% and 52% of melting point.[17] Since the expected operating temperature of the contacts of the proposed switchgear will be much higher than that of conventional switchgear the possibility of contact welding by this mode will be a significant and important consideration. The following calculation is an example of one guide to metal choice on this basis:

Environment temperature, degrees C	538
Tentative temperature rise at contacts, normal load, degrees C	100
Tentative additional rise for short time over-load and general margin, degrees C	50
Adder to convert to absolute scale, degrees C	273
Tamman temperature, degrees K	961
Melting temperature, degrees K = $\frac{961}{.37}$ = 2600	2600
Subtrahend to convert to degrees C	273
Minimum desired melting temperature, degrees C	2327

This would indicate a first choice among the refractory metals such as tungsten or molybdenum unless additional steps are taken to avoid malfunction by welding.

d. Cementing. - This refers to action of atoms of residual gas, as in a monolayer on one of the contact surfaces, sharing bonds of molecular attraction with metal atoms on each side of the interface. It is reasonable that thick films of gas would form only weak bonds, but single layers might form stronger ones. The potential for single layer films arise from the fact that at the expected operating pressures such films could form in time intervals from about one second to one year. It is anticipated that bonding even through a monolayer will be brittle. If so, this would not cause operating malfunction. However, the significant point of this portion of the examination is that a test can be taken on the basis that film formation rate is proportional to -

$$\int Pdt \qquad (P = \text{pressure},\ t = \text{time})$$

at a given temperature,[12] and decreases as the accommodation factor falls with increasing temperature.[18,19] Therefore a test taken, for example, at a pressure of 10^{-6} Torr and time of one second represents events at 10^{-12} Torr and a million seconds (about 12 days).

C. Selection of Contact Material

1. DC Interrupter

It was appropriate to evaluate contacts of molybdenum and contacts of tungsten, suitably processed, for anticipated use in the DC interrupter. Proprietary records based on work performed independently of and prior to this contract indicate either should interrupt in the required range and has been successfully used without harmful welding at the greater than the required currents in room temperature devices.

Similar evidence is displayed in a study on arc stability.[20] Figure 7 (of reference 20), for example, shows that for currents to about 50 amperes molybdenum and tungsten have much shorter average arc lifetimes than nine other metals, and to about 20 amperes molybdenum has shorter arc lifetime than tungsten.

It is anticipated that the elevated temperature of the present study will not interfere with proper function in the DC interrupter with respect to carrying ability, circuit closing ability, interruption or contact welding.

2. AC Interrupter

Analysis indicates that the high temperature at which the contacts will operate prevents the use of metals selected for normal temperature commercial

AC vacuum interrupters.

It was thought that tungsten contacts would permit current carry, make and interruption on AC at the values specified for this study, but that the chopping current level might be excessive, based on 60 cps test experience. A theoretical evaluation of this problem, in full detail, did not appear to be feasible, so the capabilities of the tungsten contacts under the combined environment were investigated experimentally at the current, voltage and frequency levels of this program.

The use of high vapor pressure electrode materials to suppress chopping in an AC interrupter has been described in reference 21. Unfortunately, this path is not open to use at the higher operating temperatures of space power switchgear, since excessive evaporation of the electrode structure would occur. The electrode thermal characteristics discussed below under interruption theory may preclude the need for such materials, however.

The choice of either tungsten or molybdenum, therefore, seems desirable from all considerations, for the AC Circuit Breaker. If it should become necessary to reduce chopping level still further, it might be possible to develop an entirely new contact material under the continuation contract NAS 3-6467. The principles and teaching of references 9 and 10 might be employed (suitable for the temperature range involved here) but plans to do so were not included in these contracts.

D. AC Interruption Theory

A current chop occurs when the temperature of the cathode spot is too low to maintain sufficient vapor pressure to permit stability of the vapor column while conducting arc current.[10] (See, specifically, columns 6 to 10 of reference 10 for bearing on all statements of this paragraph). In 60 cps tests this level, on copper contacts, is about 6 amperes, which is higher than desired. One effective factor is that the heat in the metal near the cathode spot is, in part approximating 75 percent, conducted away from that spot after arc current falls to a value too low to generate the temperature needed to maintain the required vapor pressure. If the time required for the current to fall to a desired cut-off level (less than 4 amperes, and preferably about or less than 2 amperes) were so short that the heat referred to could not be conducted away or otherwise substantially removed, the conditions necessary to maintain arcing down to that level of current would prevail. Since the rate of current decay as the current approaches a natural current zero is 33 times as fast at 2000 cps as at 60 cps, and for short time intervals and small temperature drops the heat removal by thermal conduction into the mass of contact material back of the cathode spot and by evaporation is approximately proportional to time, it appears that the temperature will drop about 1/33 as fast as at 60 cps. This would result in generation of vapor pressure and stability of the vapor column approximately comparable to that with antimony contacts as described in reference 10. This condition would result in a low "chopping current". The use of refractory metal contacts in the experimental switchgear should not, therefore, limit the application of the switch to low surge impedence systems.

III SWITCHGEAR TECHNOLOGY DEVELOPMENT

A. Contact Welding Investigation

1. Weld Testing Apparatus

a. General. For the confirmatory testing of contact material welding, several demountable, transportable vacuum capsules were constructed in which the contacts were mounted, heated, operated and subjected to a measured vacuum level. The vacuum capsule is shown in Figure 1 in the partially assembled external oven. An internal heater in the vacuum capsule was capable of heating the contacts to 750°C and thereby permitted the comparison of weld characteristics over a temperature range. The relevant mechanical features such as closing speed, opening force, and impact were representative of an operating switch rather than related to an absolute scale. However, the weld breaking under steady pull or under impact could be measured separately.

This same basic transportable vacuum capsule was used for the AC and DC interruption tests described in the latter part of this section.

The vacuum pumping equipment included a zeolite sorption pump used as the fore pump and ion pumps as the final pumps. These types were selected for cleanliness and portability. The sorption pump was preconditioned by baking at 150°C and by pumping with a mechanical pump through a liquid nitrogen trap and the zeolite trap incorporated in the sorption pump. Figure 2 is a single like sketch of the vacuum pumping system and Figure 3 is a photograph of the equipment.

The oven used for the 250°C bake-out of the ion pumps, bakeable valve, vacuum chamber and interconnecting lines was made of sections of 2" thick, low density marrinite. The 5 KW oven heaters were attached to two sides. The oven, except the base, was removable from the test set-up. Figure 1 shows the oven partially assembled around the vacuum chamber.

For the high temperature test of the contact materials the oven was modified by substituting new ends and bottom. This modification isolated the ion pumps, bakeable valve and interconnecting line from the high temperature and left only the vacuum chamber exposed to the 450 to 500°C as shown in Figure 4. Room temperature air was circulated through the tunnel under the oven bottom to cool the ion pumps.

The calibrations made by the Schenectady Instrument Services of the instrumentation used during the materials tests could all be related to the standards maintained by the Bureau of Standards in Washington. The frequency of calibration for each instrument was determined by the type of instrument, use factor and application. In general, the period between calibrations was three months. This applied to all instrumentation except cathode ray oscilloscopes which were calibrated just prior to use.

b. Vacuum capsule constructional details. The major assemblies of the vacuum capsule shown in sectional view in Figure 5 are identified as

(1) The alumina-kovar gold-copper brazed vacuum envelope.

(2) A fixed and movable electrode with contact tips that could be removed and replaced.

(3) A bellows assembly to provide for the movement of the movable electrode.

(4) A contact heater made of tantalum strip.

(5) An actuator for the movable contact.

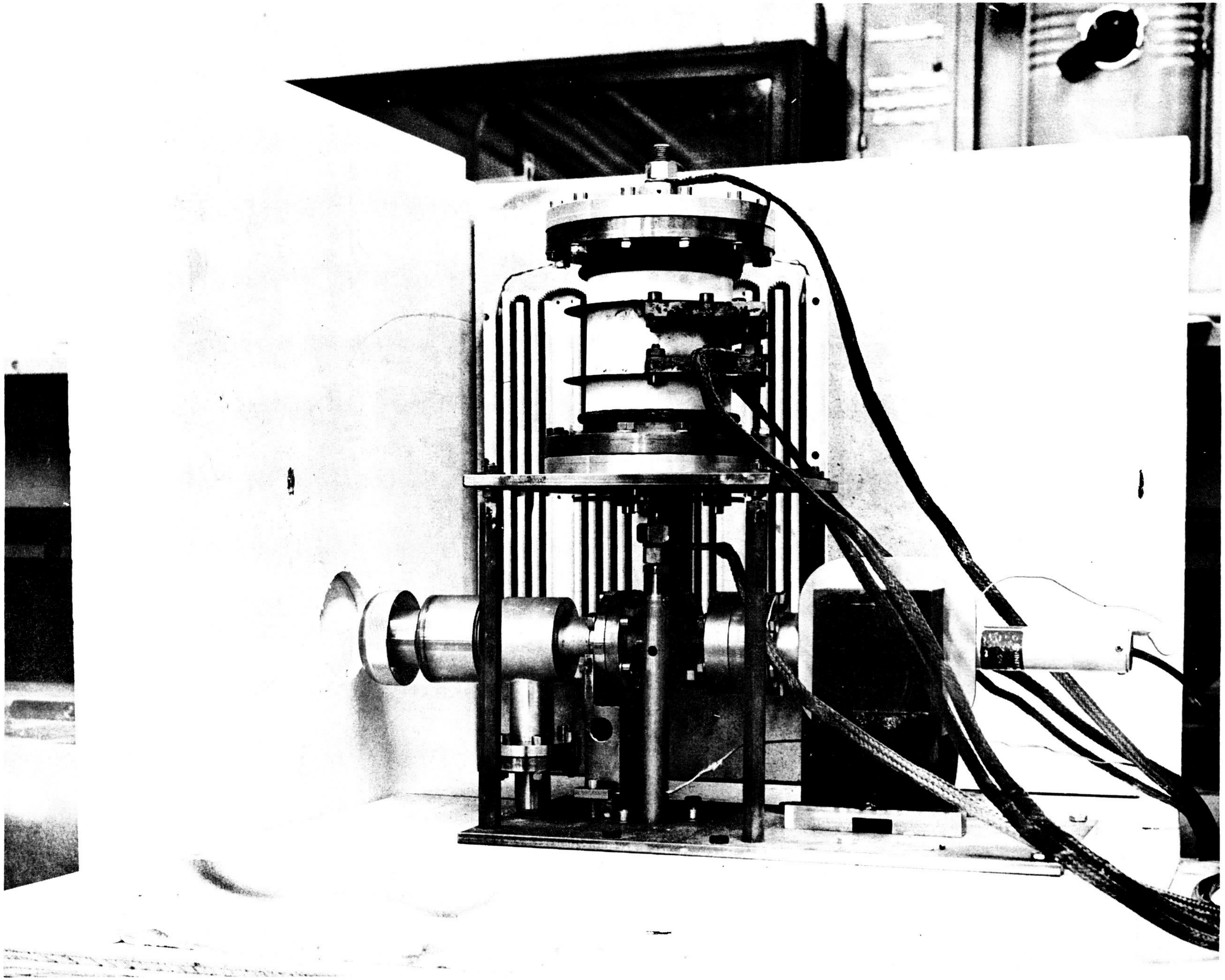


Figure 1 Vacuum Test Chamber in Partially Assembled Oven

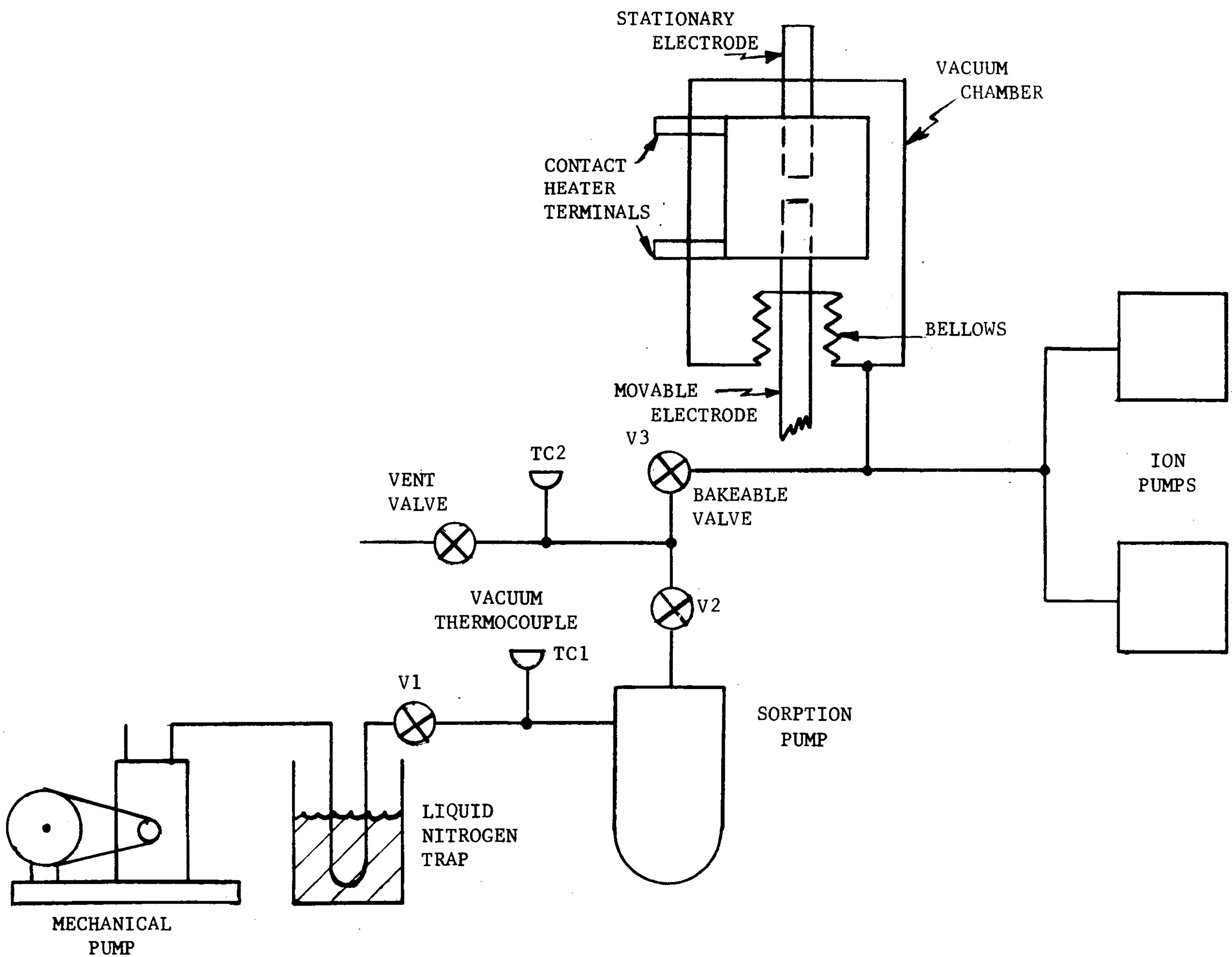


Figure 2. Sketch of Vacuum System.

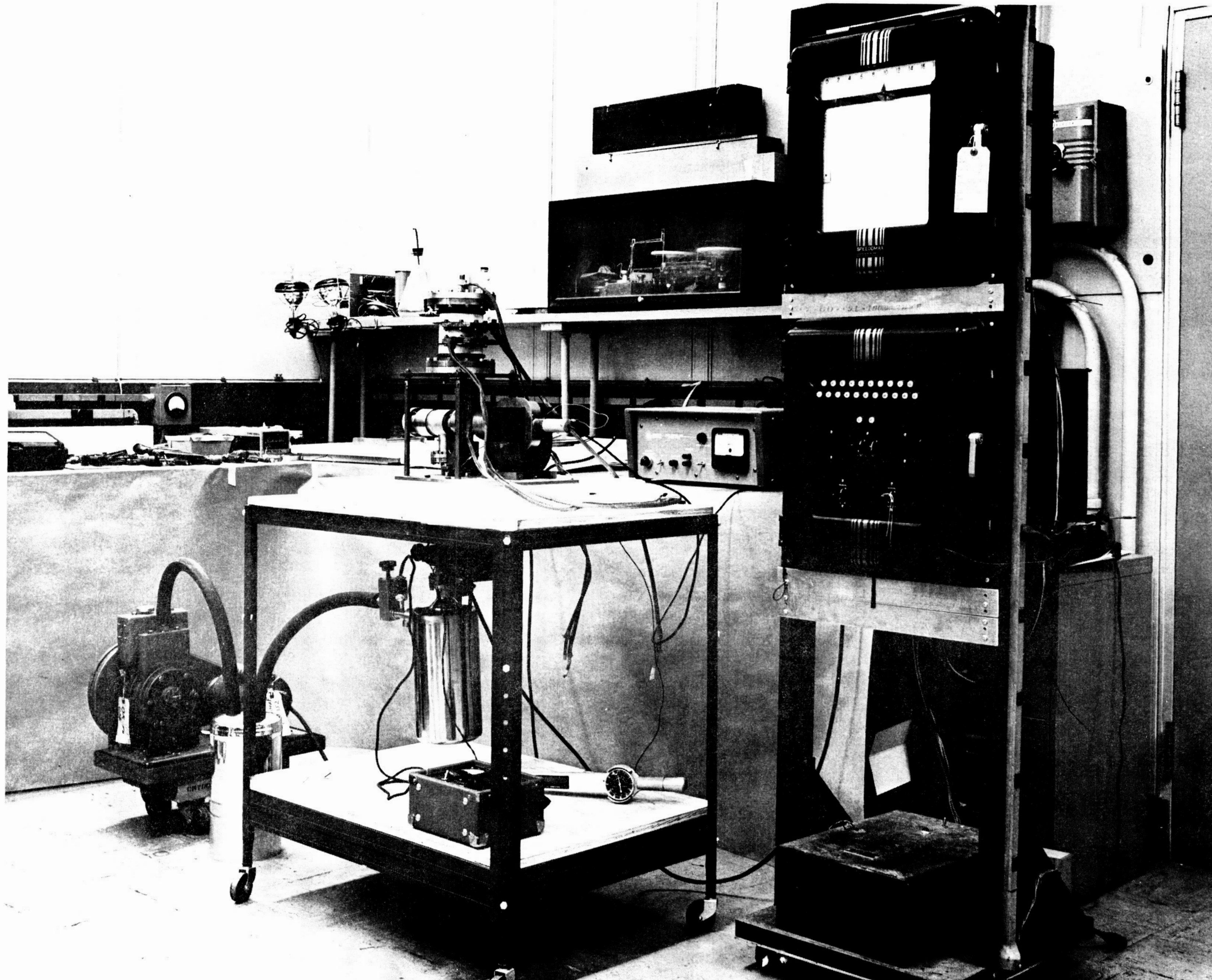


Figure 3 Equipment Set Up For Materials Welding Test

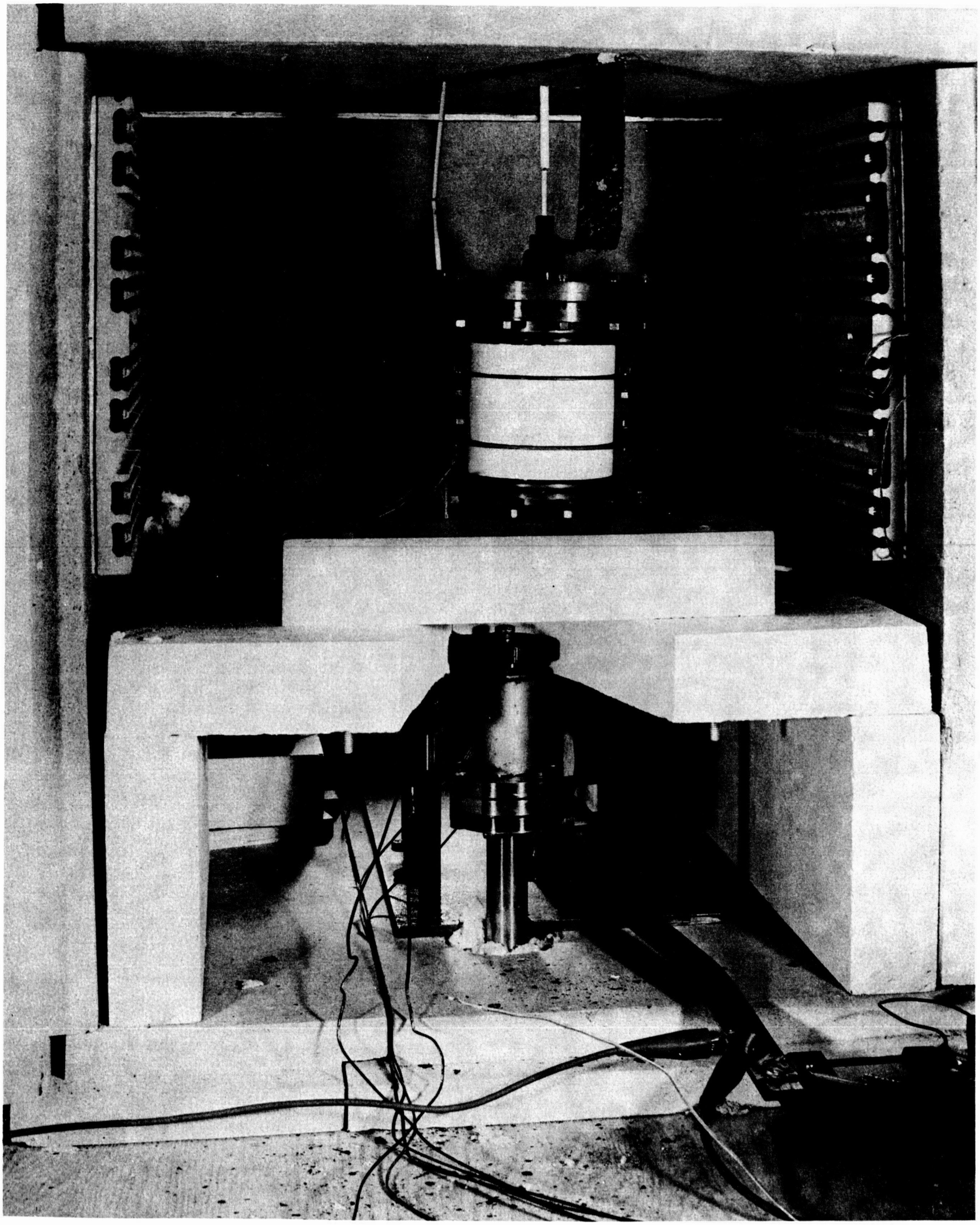


Figure 4 Vacuum Chamber in High Temperature Oven for Interruption Test

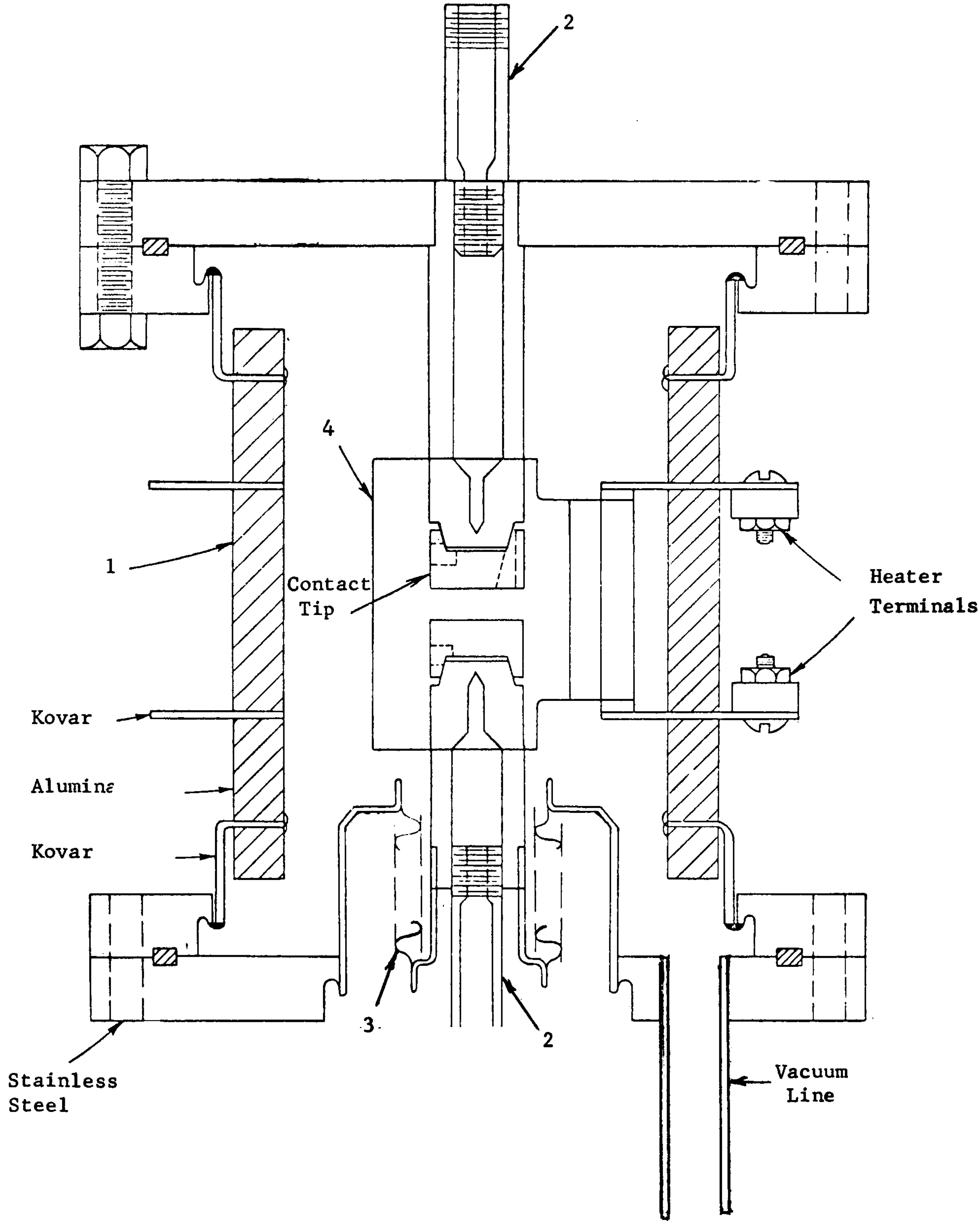


Figure 5. Vacuum Capsule

The alumina-kovar vacuum assembly is shown at (B) in Figure 6. The top and bottom stainless steel flanges (A) and (C) were inert-gas welded to the kovar spinnings at each end of the gold-copper brazed assembly. The two flanges at the center of the assembly are the electrical connections to the heater to induce the desired contact temperature, 750°C.

Figure 7 is the fixed electrode brazed to the top vacuum flange cover. A copper gasket was used between this cover and the top flange of the vacuum envelope. The end (C) of the stainless steel electrode (B) had a 5 degree taper. The contact material to be tested was brazed to a mild steel cap (D) which had a corresponding internal 5 degree taper. The contact material and cap were pressed on the electrode to assure good electrical and thermal conductivity. The greater thermal expansion of the stainless steel electrode with increased temperature further tends to increase the bond between the cap and electrode. As a further precaution a 2-56 pointed, hardened steel set screw was used to hold the contact in place.

Figure 8 shows the parts for the bellows assembly used to permit the movement of the bottom electrode and contact. All of the parts were inert gas welded except the electrode which is gold-copper brazed to part (D). The completed assembly ready for welding to the bottom cover flange is shown at (E).

The parts of the contact heater are shown in Figure 9. The strip heater is made of 0.005 inch thick tantalum. The tantalum strip was inert gas welded to the tantalum contact bars (B) and (C) and one end of each of the contact bars were welded to one of the center flanges of the alumina-kovar vacuum envelope.

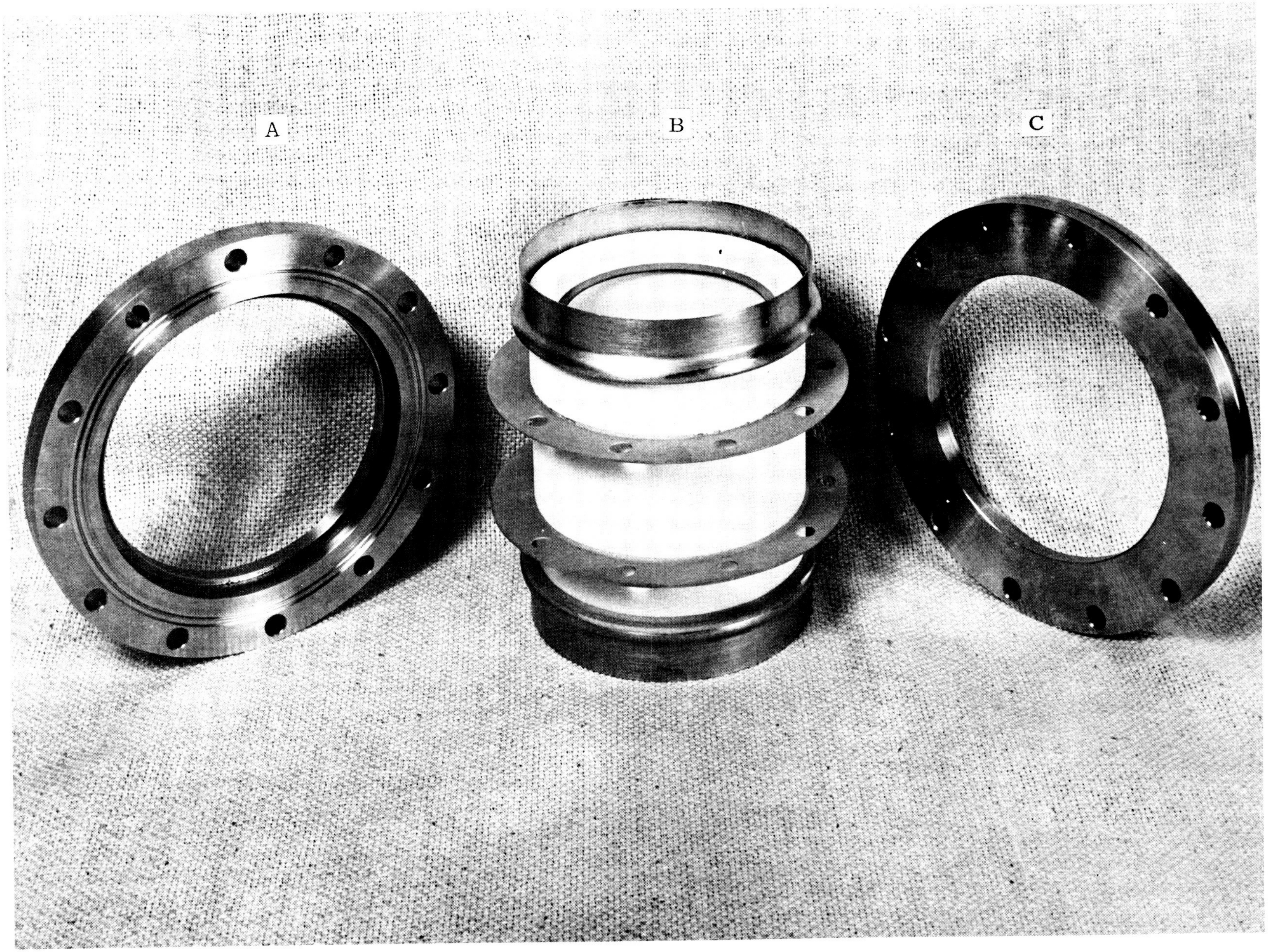


Figure 6. Vacuum Chamber Parts
A - Top Vacuum Flange
B - Alumina-Kovar Gold-Copper Brazed Envelope
C - Bottom Vacuum Flange
Photo No. 812603

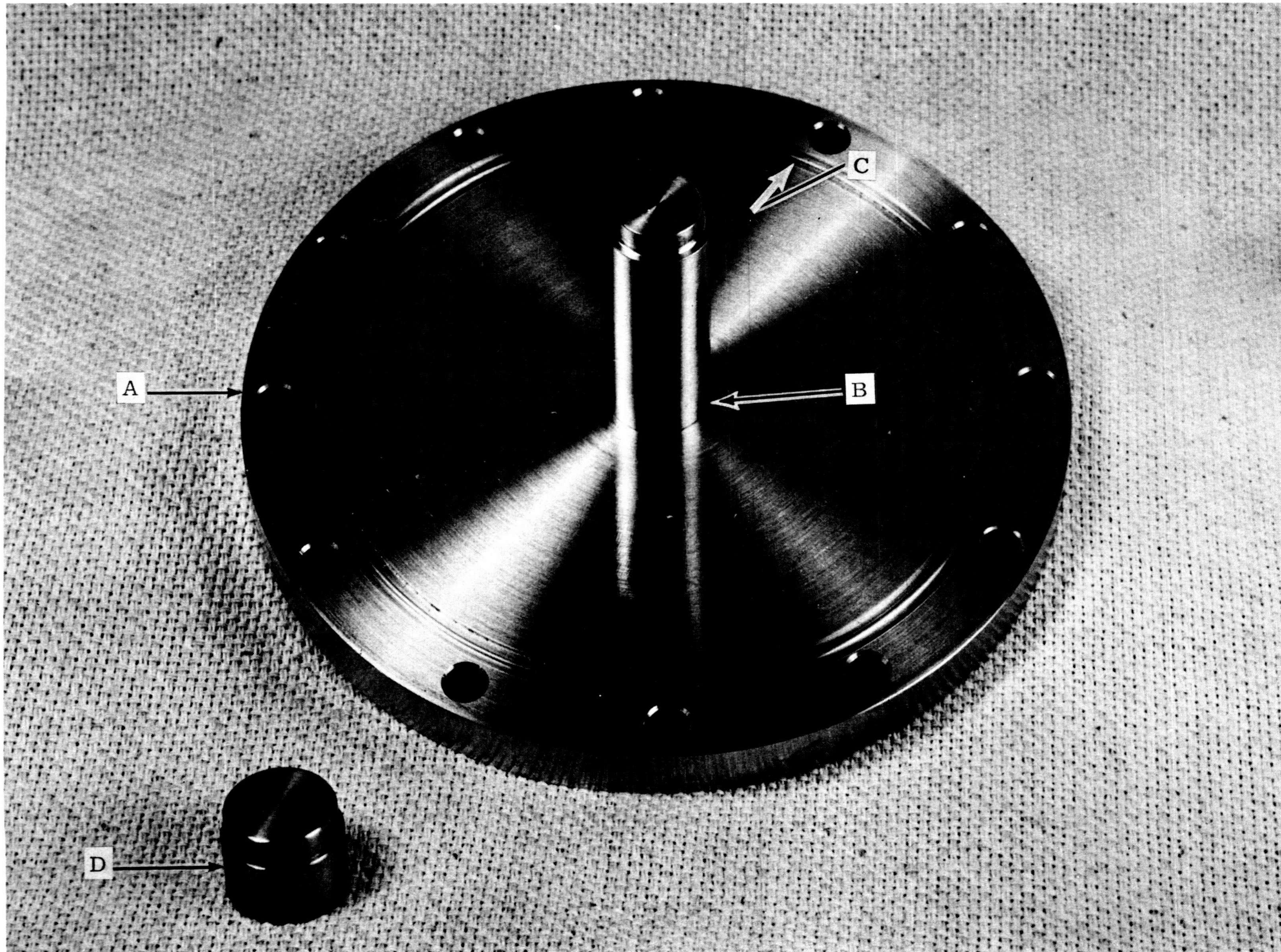


Figure 7. Top Vacuum Flange, Electrode and Contact Assembly
A - Vacuum Flange
B - Electrode
C - Tapered Electrode End
D - Contact Material Brazed to Mild Steel Internally tapered Electrode Cap

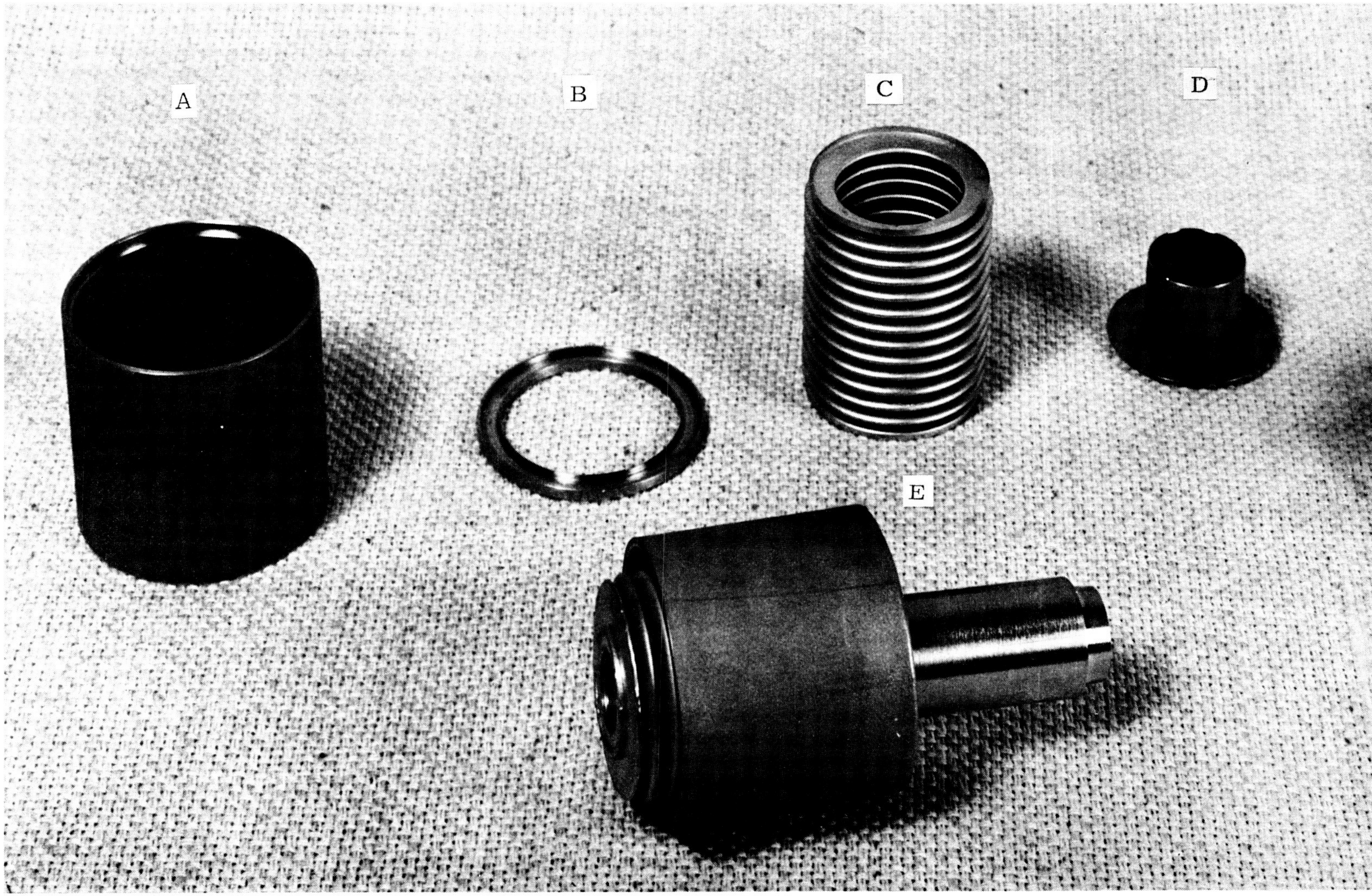


Figure 8. Movable Electrode Parts and Welded Assembly
A - Sleeve for Welding to Bottom Vacuum Flange
B - Ring Adapter Between Bellows and Part (A) above
C - Stainless Steel Bellows
D - Electrode Adapter to Bellows
E - Complete Welded Assembly
Photo No. 812602

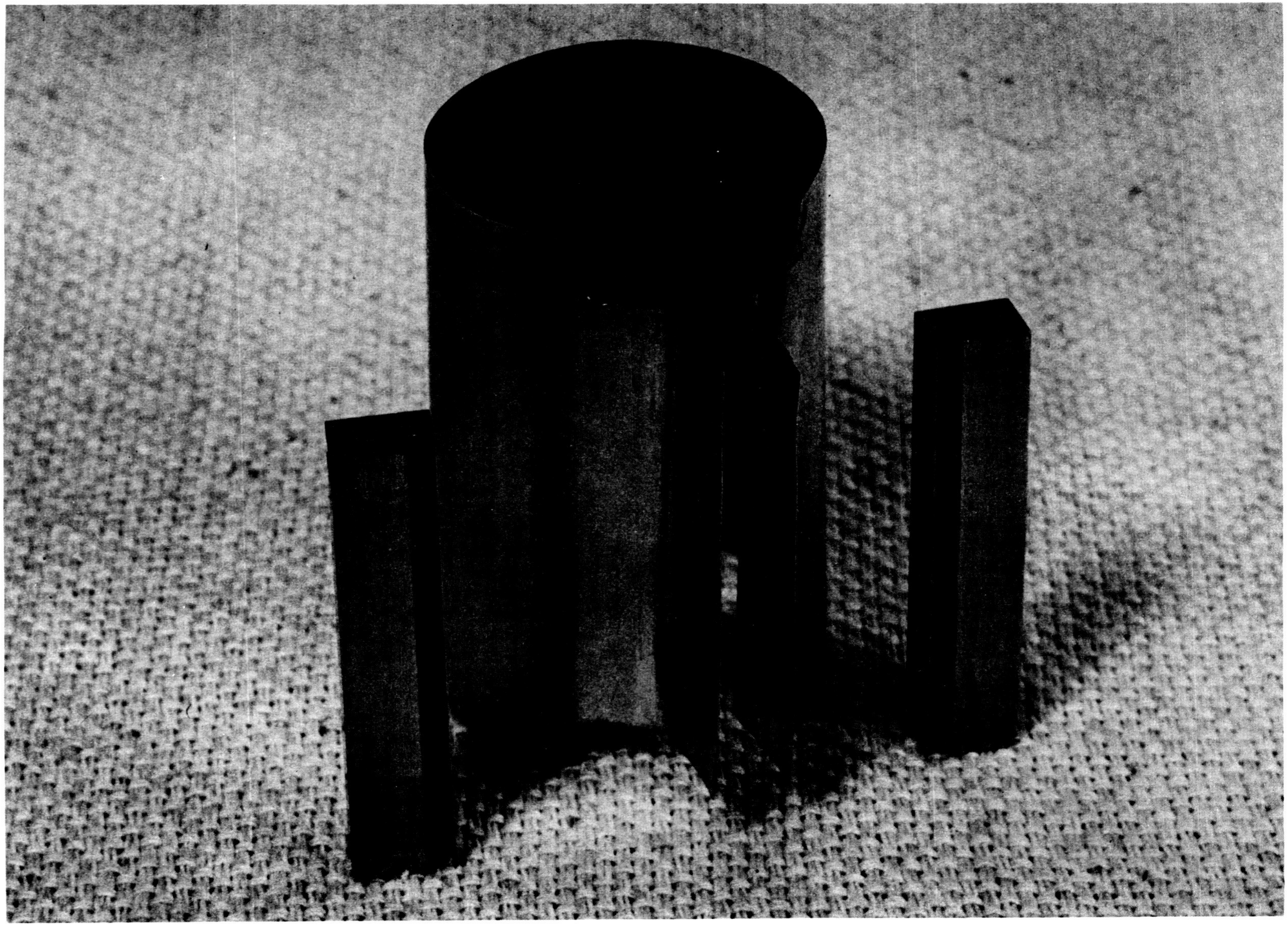


Figure 9. Contact Heater
A - Pure Tantalum Strip Heater 0.005" Thick
B - C - Pure Tantalum Contact Bars
Photo No. 812601

AC currents as high as 200 amperes were used in the heater strip to provide the temperature differential between the oven ambient, 450°C, and the estimated contact temperature of 750°C. In a preliminary test a current of 125 amperes provided a contact temperature of 610°C.

c. Contact Actuator. The operating forces of the contact actuator were representative of a commercial device. The closing force of 30 pounds was obtained from a 60 cps solenoid (A. Figure 10) operated at 80% of rated power.

The contact pressure of 20 pounds resulted from the "caged" spring (B.). The cage of this spring was adjustable to vary the contact pressure. This spring also furnished the opening impact force by accelerating the solenoid armature and linkage prior to "contact part". The solenoid armature and linkage weighs 2 pounds, 4 ounces.

The counter-balance spring (c) opposes the force of 15 pounds due to atmospheric pressure on the moveable contact when the contacts were open. This spring also furnished an opening force of 8 pounds at the time of "contact part". Calibration curves of the "caged" and "balance" springs are shown in Figure 11.

To prevent degradation of the spring constant of either of the two springs they were located below the oven as shown in Figure 12. A thin wall stainless steel tube connected the actuator to the contact electrode. This reduced the heat conducted from the vacuum chamber to the actuator. The springs were at a temperature of approximately 40°C.

2. <u>Test Procedures</u>

The pump-down routine found effective during the many low and high

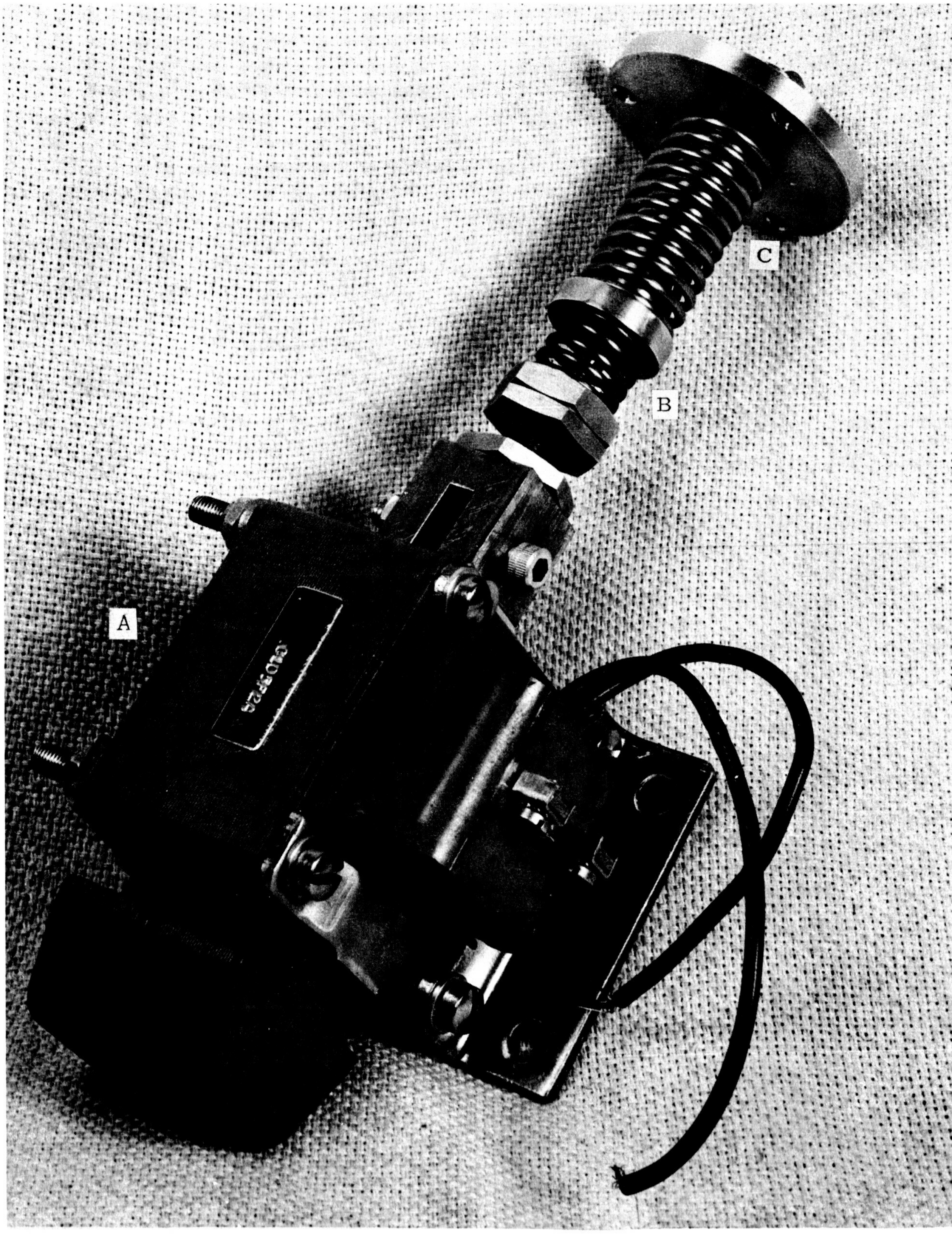
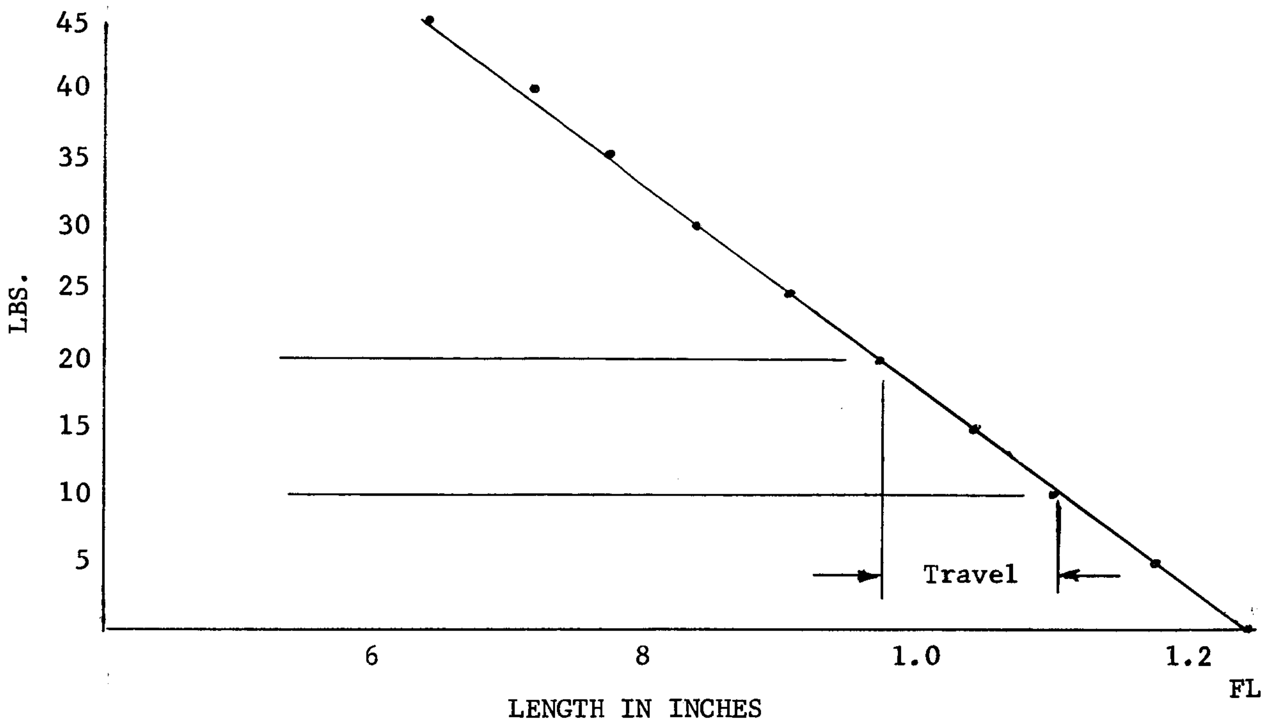
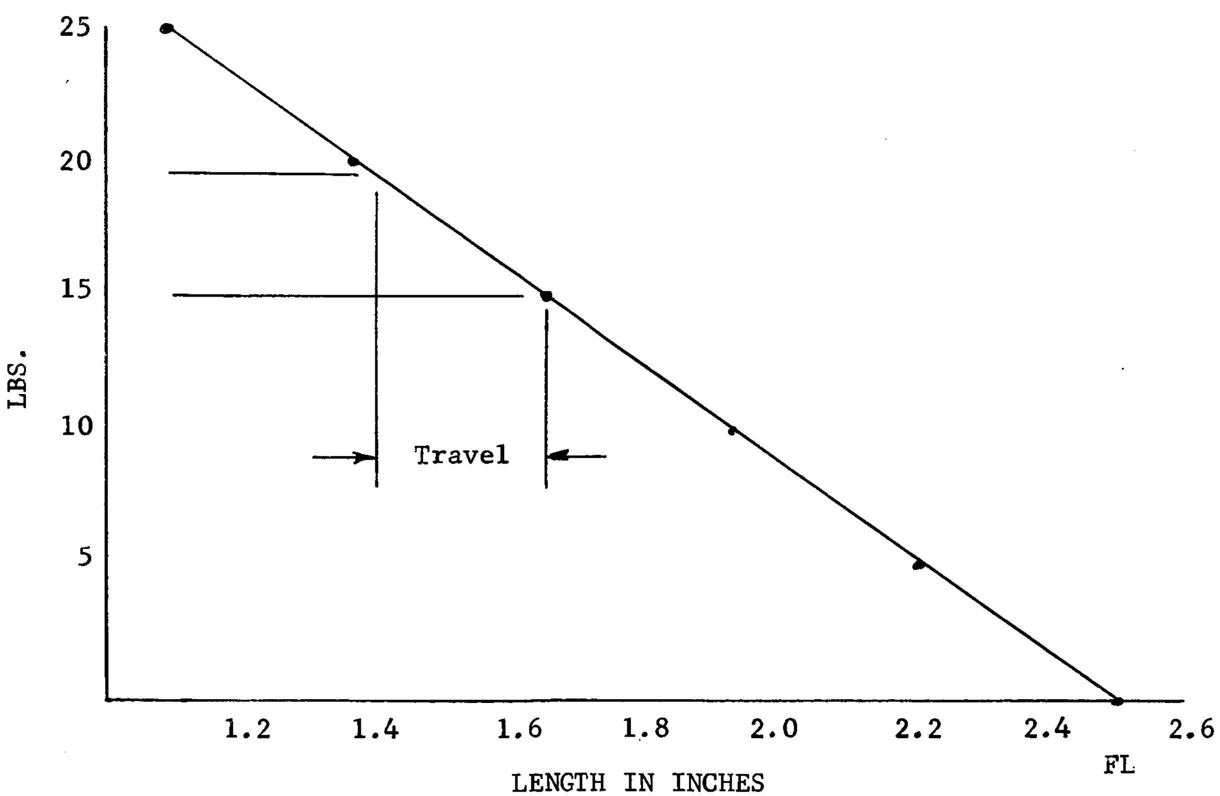


Figure 10. Contact Actuator
A - AC Solenoid
B - Caged Contact Pressure Spring
C - Counter Balance Spring
Photo No. 813101



CONTACT PRESSURE SPRING CALIBRATION



BALANCE SPRING CALIBRATION

Figure 11

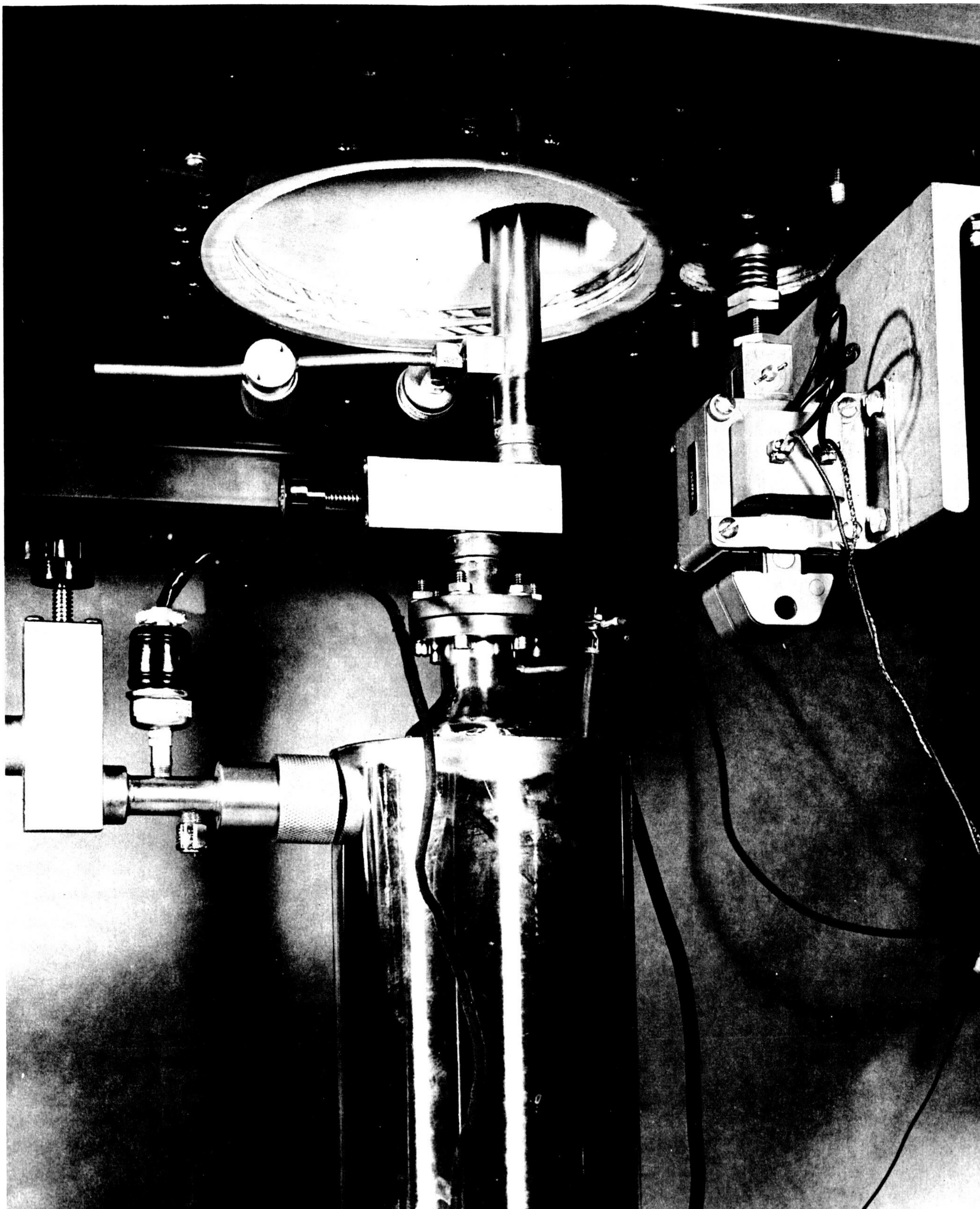


Figure 12 View Below Test Table Showing Contact Actuator, Sorption Pump and Vacuum Connections

temperature bake-outs of the system was the following: (The symbols refer to Figure 2).

The sorption pump was preconditioned over night by a bake-out and pump-down with the mechanical pump. The liquid nitrogen vapor trap was filled at the start and was still 1/4 full at the end of the preconditioning period. The vent valve and valve V2 were closed. Valves V1 and V3 were open. After approximately 15 hours of pumping the pressure indicated at TC-1 in the section being pumped would be 4 to 5 microns. V2 was then opened and the pressure at TC-2 was 25 to 35 microns. After 15 to 25 minutes with the sorption pump cooling to room temperature and the mechanical pump running, the pressure at TC-2 would be 5 to 10 microns. At this time the sorption pump was filled with liquid nitrogen. After approximately 30 minutes the pressure indicated at TC-2 would be below zero on the instrument scale. Valve V1 was then closed. In 30 minutes the ion pumps were turned on and would indicate in the range of 1×10^{-4} Torr. When the ion pumps indicated less than 5×10^{-5} Torr. Valve V3 was closed and the closure checked through the vent line and vent valve with helium. No change in the pump-down rate indicated a tight closure of V3. When the pressure reached 1×10^{-5} Torr the 250°C low temperature bake-out of the system would be started. This bake-out included the bakeable valve and ion pumps and was conducted in the large oven shown partially assembled in Figure 1. The data shown in Tabulation 1 is typical of a low temperature bake-out. The temperatures were continuously recorded on a multipoint Leeds and Northrup temperature recorder. The pressure in the system was obtained from the ion pump power supply instrument which indicated ion pump current and was calibrated in Torr.

CONTACT MATERIAL TEST

SYSTEM BAKE-OUT 250°C (482°F) May 23, 1964

TEMPERATURE °F

TIME	VALVE T2	PUMP MAGNET T3	CONTACTS BOTTOM T4	CONTACTS TOP T5	TOP FLANGE T6	HEATER CONNECTION T7	OVEN AIR T8	PRESSURE TORR.
9:45 a.m.	160	84	84	84	84	84	84	5×10^{-5}
10:03	150	95	105	110	132	135	-	2×10^{-6}
10:40	160	95	150	220	280	300	420	8×10^{-6}
11:20	230	105	275	360	420	435	500	4×10^{-6}
11:50	245	105	345	440	490	495	540	4×10^{-6}
12:20 p.m.	265	105	410	510	550	545	565	5×10^{-6}
12:50	375	152	460	540	575	550	565	1×10^{-5}
1:20	400	200	500	570	600	585	590	1×10^{-5}
1:50	370	170	510	600	620	610	612	1×10^{-5}
2:00	360	150	525	600	630	600	615	9×10^{-6}
* 2:20	330	110	520	590	580	530	470	5×10^{-6}
2:30	300	95	500	560	535	470	390	3×10^{-6}
3:00	260	95	420	460	420	360	290	9×10^{-7}
● 3:30	190	90	260	360	320	260	-	4×10^{-7}

CONDITIONS: VALVES V2 - V3 OPEN VENT-V1 CLOSED
TUNGSTEN CONTACTS CLOSED 20 LBS. PRESSURE
ION PUMP NOT EXPOSED TO TOTAL HEAT

* OVEN HEAT OFF
● OVEN OPENED

TABULATION 1

The temperature-pressure data taken during the various high temperature tests varied with the length of time that the system had previously been at high temperature and low pressure. The data in Tabulation 2 was an early high temperature evacuation test. This test was discontinued due to a leak in the vacuum system.

Two methods of assessing the strength of the weld between the contacts was planned. The first was without impact. The contacts were held closed until after power was removed from the actuator solenoid. The mechanism then being slowly released. With this procedure a weld of the contacts would hold the contacts closed. A force gage that would retain the measure of pounds pull at the instant of weld breakage was to be used to part the contacts. Assuming that welding did occur and the strength of the weld was measured by this method, an effort to break subsequent welds by the actuator impact would then be made.

The mode of contact welding classified as "cold welding" or "cohesion" in section II-B of this report was considered first. If this mode of welding occurred, it could be determined by closing the contacts under 20 pounds pressure during an early stage of the high temperature-evacuation of the vacuum chamber, the contacts being held closed for the duration of the bake-out and pumping period. Tabulation 3 shows the results of such a successful test.

This test was performed first with tungsten contacts. The material for the contacts was obtained from the General Electric Switchgear Laboratory. The material was not single crystal or super refined material but was classified as a commercial grade of tungsten. The contact tips and soft iron caps Figures 5 and 7) were machined in the A.T.L. The finished parts were furnished

TUNGSTEN CONTACT MATERIALS TEST

April 15, 1964

TEMPERATURE °C

TIME	VALVE T1	PUMP MAGNET T2	CONTACTS TOP T3	CONTACTS BOTTOM T4	PRESSURE TORR.
11:15 a.m.	Heat on	-	-	-	10^{-6}
11:30	115	40	55	55	10^{-5}
11:40	140	40	95	95	2×10^{-5}
11:45	160	40	120	120	2×10^{-5}
11:50	200	40	150	150	10^{-4}
11:55	225	45	185	185	5×10^{-5}
12:05 p.m.	290	55	250	250	2×10^{-6}
12:16	380	70	350	350	5×10^{-6}
12:22	400	70	375	372	10^{-5}
12:30	430	75	420	415	10^{-5}
12:32	440	75	430	427	2×10^{-5}
12:35	435	-	455	455	2×10^{-5}
12:42	448	-	505	500	2×10^{-5}
12:50	448	-	530	535	2×10^{-5}
12:55	445	-	540	555	2×10^{-5}
1:05	445	-	542	550	2×10^{-5}
1:10	440	-	555	570	3×10^{-5}
1:18	450	-	588	610	5×10^{-5}
1:25	Closed Valve. Ion Gage Dropped to 5×10^{-4} Torr. All Heaters off.				

TABULATION 2

TABULATION 3

CONTACT MATERIAL TEST

SYSTEM BAKE-OUT 543°C (1000°F)

May 4, 1964

TEMPERATURE °F

TIME	VALVE T2	PUMP MAGNET T3	CONTACTS BOTTOM T4	CONTACTS TOP T5	TOP FLANGE T6	PRESSURE TORR.
10:00 a.m.			Oven on			5×10^{-6}
10:05			All Below 200°F Off			2×10^{-5}
10:10	160	100	160	150	180	5×10^{-4}
10:15	180	100	240	200	20	2×10^{-5}
10:20	250	110	280	240	280	5×10^{-4}
10:30	370	120	340	320	395	7×10^{-5}
10:40	390	130	430	420	440	5×10^{-5}
10:55	620	170	590	580	665	1×10^{-4}
11:05	655	190	720	700	710	5×10^{-5}
11:15	770	220	920	850	830	3×10^{-5}
11:29	770	135	1080	990	865	3×10^{-5}
11:36	-	-	-	-	-	3×10^{-5}
11:45	790	260	1150	1030	895	3×10^{-5}
12:00 Noon	815	280	1225	1100	930	5×10^{-5}
12:15	830	300	1235	1105	940	5×10^{-5}
12:30	835	305	1285	1135	950	5×10^{-5}
1:00 p.m.	300	330	1290	1145	925	4×10^{-5}
1:07	822	335	1282	1140	945	3×10^{-5}
2:00	860	355	1290	1150	975	4×10^{-5}
2:10	830	355	1310	1165	955	3×10^{-5}
3:40	820	365	1410	1235	965	3×10^{-5}
4:30	810	365	1400	1200	950	-
6:00	810	360	1410	1230	950	2×10^{-5}
6:02	810	360	1320	1180	950	2×10^{-5}
7:00	770	360	1220	1145	900	1.5×10^{-5}
8:05	815	355	1340	1175	945	1.8×10^{-5}
8:18	840	350	1340	1180	945	1.8×10^{-5}
8:38	750	345	1330	1160	890	1×10^{-5}
8:49	730	340	1300	1140	875	1×10^{-5}

CONDITIONS: VALVE V3 CLOSED
TUNGSTEN CONTACTS CLOSED 20 LBS. PRESSURE
VACUUM CHAMBER IN SMALL OVEN

to the Schenectady Research Laboratory for vacuum processing and brazing of the tungsten contacts to the soft iron caps.

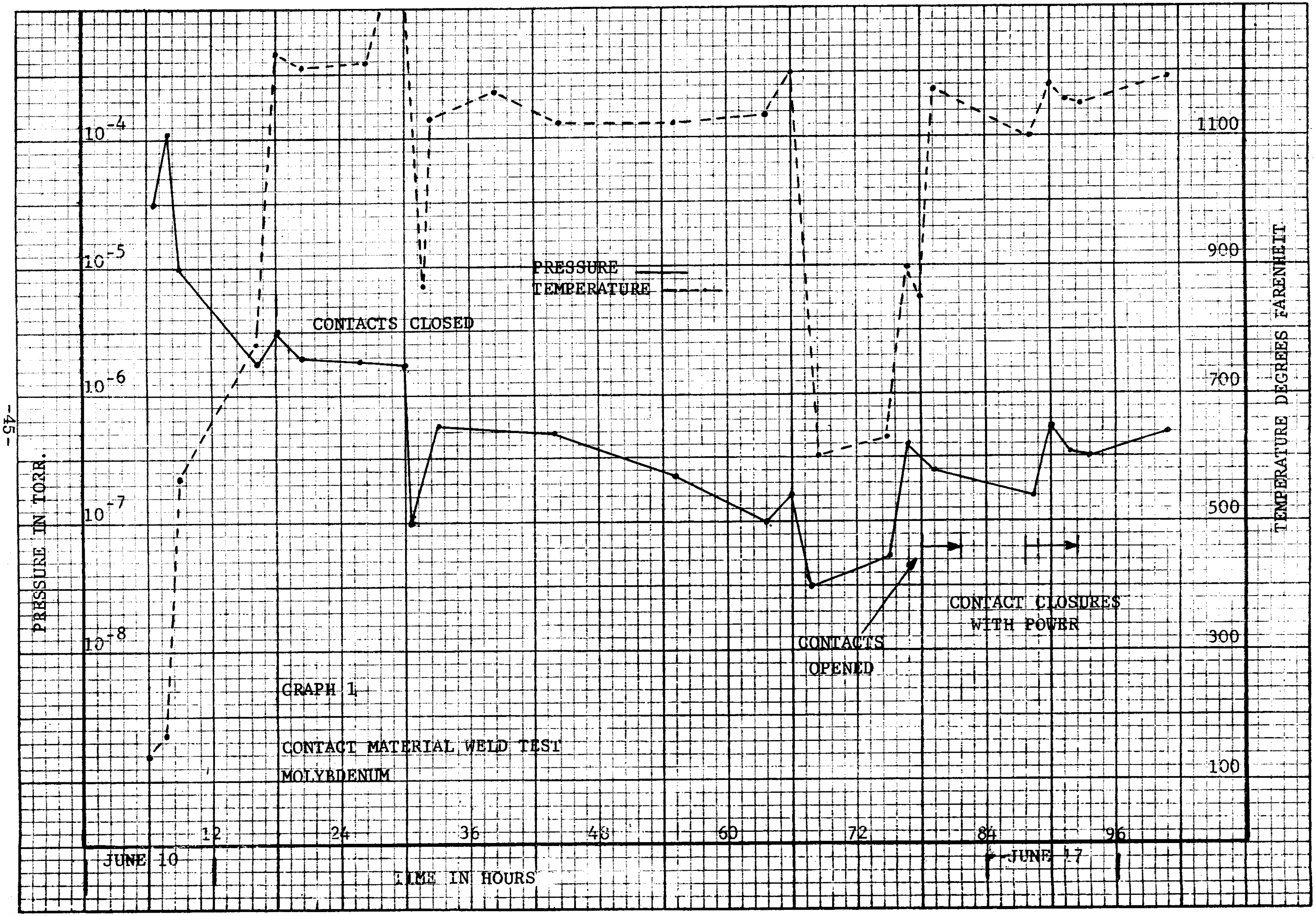
The vacuum processing operation was a procedure for removing the sorbed gases in the metals. The pieces were baked at 2000°F in a 10^{-4} Torr vacuum for one hour. A brazing material of gold, copper, and nickel was used in a hydrogen atmosphere to attach the tungsten tip to the iron cap.

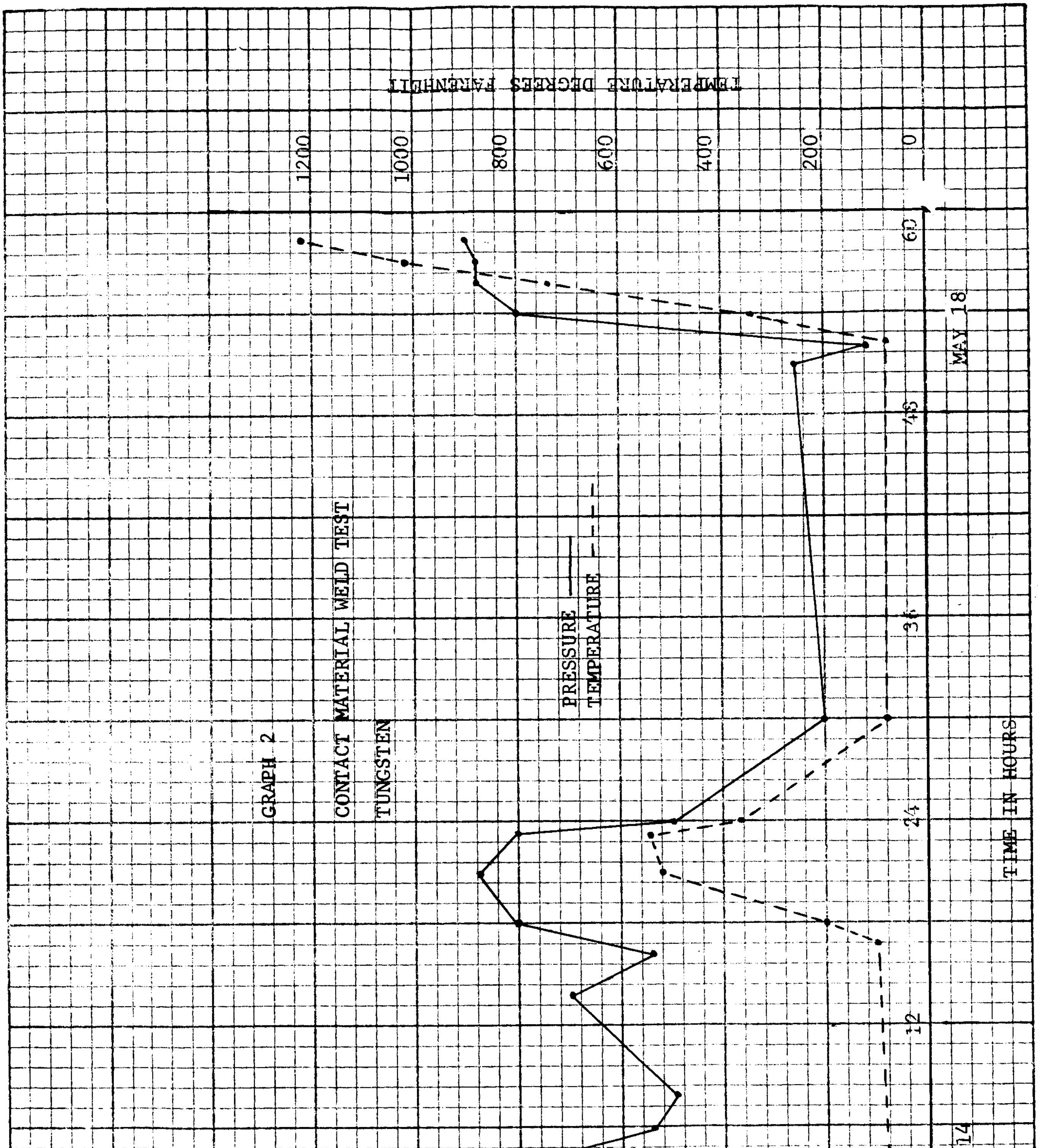
During the various high temperature-evacuation attempts the contacts were closed for periods of time ranging from 8 hours to 95 hours. Graph 1 shows the temperature and pressure profile during an 8 day period. The molybdenum contacts in the chamber were held closed for 5 days under the 20 pound pressure of the caged spring on the actuator. The contacts were then opened slowly by hand after de-energizing the solenoid and showed no tendency to adhere or stick.

This same opening procedure was used on tungsten contacts. Graph 2 shows the variation of temperature and pressure over a 5 day period with the tungsten contacts in the chamber. The tungsten material showed no tendency to weld or stick by this mode.

The mode of contact welding defined as "melting of the contact material with consequent freezing and recrystallation across portions of the original interface" was investigated with molybdenum contacts.

This mode can occur when the contacts close on high current, especially with contact bounce. The tests were conducted at temperatures in the range from 610 to 700°C and in a vacuum ranging from 7.5 to 2 x 10^{-7} Torr. The pressure and temperature for the closure tests is indicated on Graph 1.


PRESSURE IN TORR.
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
TEMPERATURE DEGREES FARENHEIT
1100
900
700
500
300
100
PRESSURE
TEMPERATURE
CONTACTS CLOSED
CONTACTS OPENED
CONTACT CLOSURES WITH POWER
GRAPH 1
CONTACT MATERIAL WELD TEST
MOLYBDENUM
12
24
36
48
60
72
84
96
JUNE 10
JUNE 17
TIME IN HOURS


GRAPH 2
CONTACT MATERIAL WELD TEST
TUNGSTEN
PRESSURE
TEMPERATURE
TEMPERATURE DEGREES FAHRENHEIT
1200
1000
800
600
400
200
0
PRESSURE IN TORR.
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
TIME IN HOURS
12
24
36
48
60
MAY 14
MAY 18

The contacts were closed by the actuator shown in Figure 10. The AC solenoid was operated at 80% of rated power to reduce the impact on the contacts and avoid damage to the ceramic vacuum enclosure. The number of closures made, the current and voltage for each closure, chamber pressure, contact temperature, and rise in chamber pressure during closure are listed in Tabulation 4.

During all the tests there were no indications of welding or sticking with contacts being opened slowly by hand.

WELD TEST
CONTACTS CLOSING
DC POWER

June 16, 1964

MOLYBDENUM

Operation	DC Volts	DC Amps	Pressure μA	Pressure Torr	Rise μA	Rise Torr	Temperature Contacts °C	Temperature Ambient Air °C
1	12	20	89	$7x10^{-7}$	200	$1.7x10^{-6}$	680	471
2	12	20	90	$7x10^{-7}$	100	$8x10^{-7}$	685	477
3	12	20	92	$7x10^{-7}$	None		685	477
4	12	20	92	$7x10^{-7}$	None		685	477
5	12	20	95	$7.5x10^{-7}$	100	$8x10^{-7}$	685	477
6	12	20	95	$7.5x10^{-7}$	99	$8x10^{-7}$	680	477
7	12	20	95	$7.5x10^{-7}$	None		685	477
8	12	20	90	$7x10^{-7}$	None		685	471
9	12	20	90	$7x10^{-7}$	None		685	471

Contact heater current 135 amperes, oven voltage 125.

Solenoid 60 , operating voltage 90.

June 17, 1964

Operation	DC Volts	DC Amps	Pressure μA	Pressure Torr	Rise μA	Rise Torr	Temperature Contacts °C	Temperature Ambient Air °C
1	12	22	47	$3.7x10^{-7}$	48	$3.7x10^{-7}$	610	460
2	12	22	50	$4x10^{-7}$	64	$5x10^{-7}$	615	466
3	12	22	64	$5x10^{-7}$	67	$5.5x10^{-7}$	620	471
4*	12	22					625	477
5	12	22	87	7.10^{-7}	—		630	485
6	12	22	87	$7x10^{-7}$			615	488
7	12	22	87	$7x10^{-7}$			630	463
8	12	22	87	$7x10^{-7}$			622	457
9	12	22	87	$7x10^{-7}$			622	457
10	12	22	87	$7x10^{-7}$			620	457
11	12	22	87	$7x10^{-7}$			617	457
12	12	22	87	$7x10^{-7}$			610	451
13	12	22	88	$7x10^{-7}$	—		610	451
14	12	22	88	$7x10^{-7}$			630	479
15	12	22	88	$7x10^{-7}$			625	471
16	12	22	88	$7x10^{-7}$			625	471
17	12	22	88	$7x10^{-7}$			625	471
18	12	22	88	$7x10^{-7}$			625	471
19	12	22	88	$7x10^{-7}$			622	468
20	12	22	80	$6.5x10^{-7}$	—		622	468

*Thermocouple removed from top contact.

TABULATION 4

WELD TEST (cont'd.)
June 18, 1964

Operation	DC Volts	DC Amps	Pressure µA	Pressure Torr	Rise µA	Rise Torr	Temperature Contacts °C	Temperature Ambient Air °C
1	12	22	22	2×10^{-7}	—		622	421
2	12	22	25	2×10^{-7}	—		622	450
3	12	22	40	3.2×10^{-7}	—		630	463
4	12	22	50	4×10^{-7}	—		630	463
5	12	22	50	4×10^{-7}	—		635	466
6	36	5	60	5×10^{-7}	—		640	485
7	36	19.9	75	6×10^{-7}	—		640	485
8	36	19.9	75	6×10^{-7}	—		640	485
9	125	6.9	65	5×10^{-7}	—		625	471
10	125	6.9	65	5×10^{-7}		—	630	471
11	125	15	65	5×10^{-7}		—	630	471
12	125	15	76	6×10^{-7}		—	635	471
13	125	20	76	6×10^{-7}		—	635	468
14	125	20	76	6×10^{-7}		—	635	468
15	125	20	76	6×10^{-7}		—	635	468
16	125	10	76	6×10^{-7}		—	635	470
17	125	20	80	6.5×10^{-7}		—	640	471
18	125	25	74	6×10^{-7}		—	635	477
19	125	25	80	6.5×10^{-7}		—	640	479
20	125	30	85	7×10^{-7}		—	640	485

TABULATION 4

B. High Power Interruption Test

Switchgear testing at high power levels has, in general, involved short term rated test devices rather than operation at full scale steady-state current. In the early days of such testing high current rotary generators supplied the power for most interruptions. It is not possible, of course, to find traditional switchgear testing means for high frequency AC devices, such as those under consideration in this program, and for high voltage DC devices in our nominal current range. The table below shows a comparison of full load testing, compound testing, and simple capacitor discharge testing for the ratings required in the space power switchgear program:

- Actual Full Load Testing

    1,200 KVA, 2,000 cps Tuned Circuit,
    50 KW Input, 1,000 V

    200 KW DC Supply, 20 A, 10,000 V

- Compound Discharge Testing

    Steady-state 1,200 A, 10 V, 2,000 cps,
    1,000 V Discharge on Opening

    Steady-state 20 A, 10 V, DC,
    10,000 V Discharge on Opening

- Simple Capacitor Discharge Testing

    30,000 joule, 1,200 KVA, 2,000 cps Discharge
    5-10 cycles for 10% Decay

    30,000 joule, 200 KW DC Discharge, 10-15 MS
    for 10% Decay

It may be seen that very massive apparatus is needed for full load testing. Compound testing is complicated by a high current, low voltage preheating supply and a high voltage, low current supply to simulate the recovery voltage with precisely timed switching. The simple capacitor discharge method, when a large capacitor bank is available, makes it possible to generate many cycles of high frequency discharge with little energy decrement or many milliseconds of essentially constant current discharge. The high powered discharge apparatus used in the early tests at Philadelphia is shown in Figure 13. The adaptation of this equipment to run the DC test as well as the high frequency AC test provided a considerable economy in the test program by eliminating duplication of test calibration procedures, and also by eliminating the cost of preparing a separate high voltage DC test facility and vacuum test chamber.

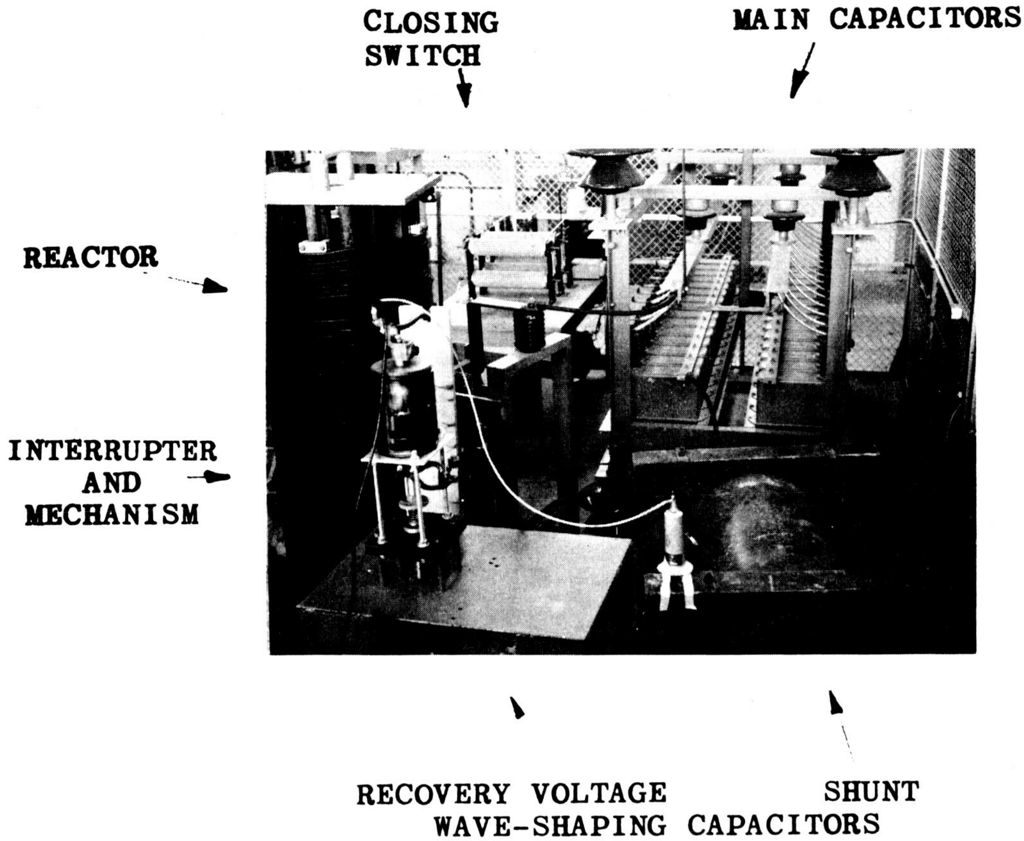
1. AC Interrupter Evaluations

a. 2000 vs. 60 cps Evaluation. The evaluation of the effect of the 2000 cps power on the interruption mechanism of a vacuum breaker was determined at room temperature with a standard commercial vacuum interrupter. This permitted the direct comparison of the performance at 2000 cps to the 60 cps performance of a commercial device.

These interruption tests were performed at the General Electric Switchgear Laboratory in Philadelphia. The test apparatus and circuit diagram are shown in Figure 13. The main capacitor bank was tuned by the current limiting reactor to provide a 2000 cps discharge frequency. The decay time constant of the circuit was 3.6 milliseconds. About 75% of the effective resistance, which caused this decay, was in the main storage capacitor bank..

The decay time-constant of the circuit was not objectionable in this case since the test device clears in less than a millisecond after contacts part. This corresponds to a contact separation of 1/16 inch or less at the time of interruption.

There was considerable variation (as much as 1.5 milliseconds) of the time from trip impulse to contact parting. This variation was due to the



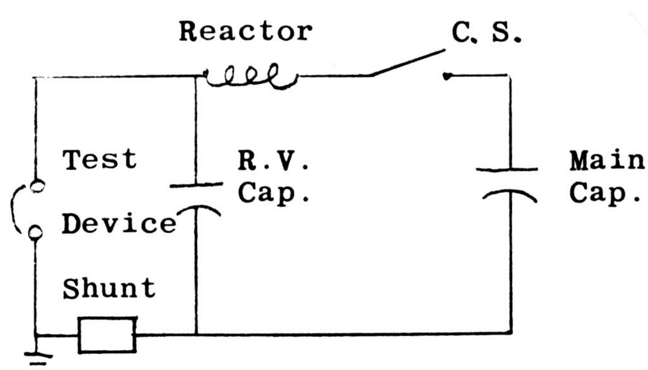


Figure 13. Circuit and Equipment for 2000 cps ATL Interruption Investigation.

operation of the trip latch on this particular mechanism. As a result of this variation and the current decay there was a variation of the current at contact parting for the various interruption tests.

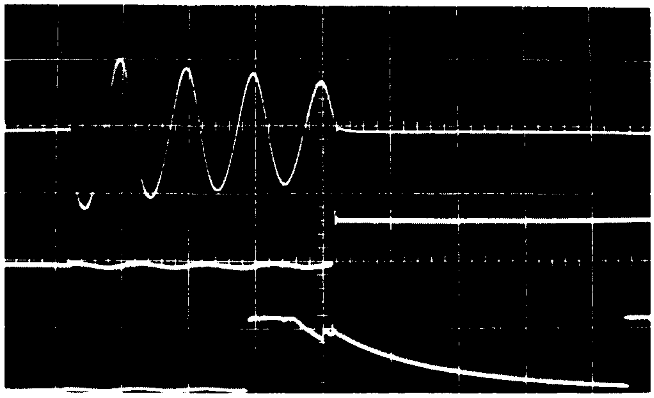
A "contact part indication" was recorded for all of the tests. The first step variation in this trace on the oscillograms of Figures 14 thru 17 is the indication of "contact part". The latter discontinuities in the trace were caused by the bounce of the contact part indicator switch.

The main storage capacitor bank could be charged to 14 KV peak. For tests 2 thru 8, the bank was charged to 3.5 KV peak. The peak current at "contact part" for these tests (2 thru 8) averaged around 1800 amps. The peak current for test #1 at contact part was 2900 amperes. The bank voltage was not recorded for this test but was known to be above 3.5 KV peak.

Peak recovery voltages of the order of 4000 volts were recorded with recovery frequencies of 167 KC to 780 KC. The divider used to measure the recovery voltage did not correctly record the amplitude of the first peak of the recovery voltage at these frequencies. The correct amplitude of the first peak is 70% of the deflection times the calibration. No correction is required for the steady-state voltage.

The results of these tests at 2000 cps current greatly exceeded the 60 cps application requirement of the vacuum interrupter used. It was felt unnecessary to study in detail the dielectric recovery characteristics at 2000 cps. This was not considered necessary because the device interrupted the circuit with very small contact separation and with very high recovery voltage frequency and amplitude.

#1



3400A/cm

5000V/cm

0.5ms/cm

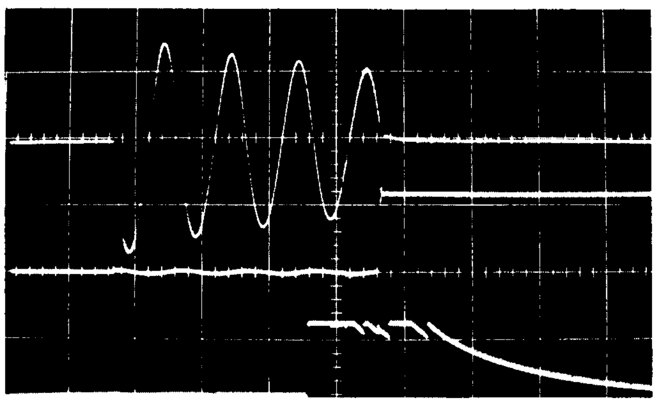
CONTACT PART
INDICATION

#2a

Current thru
Breaker

Voltage across
Breaker

Breaker Contact
Part Indication



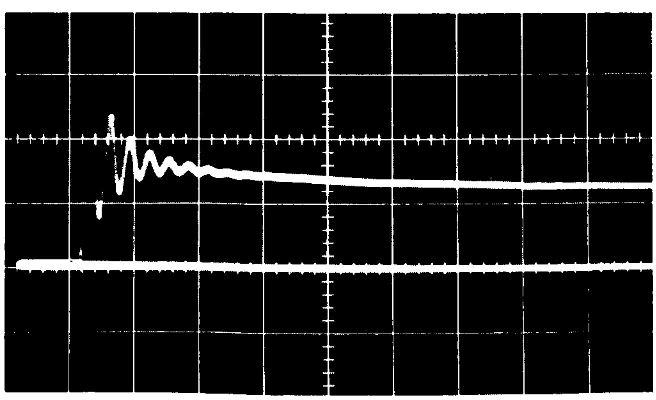
1700A/cm

2000V/cm

0.5ms/cm

#2b

Voltage across
Breaker at Clearing

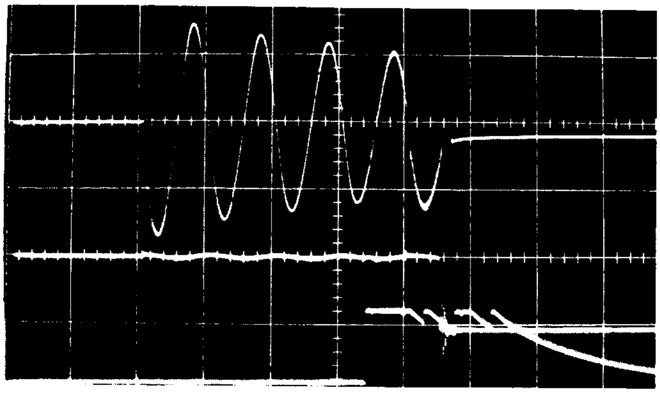


2000V/cm

20μs/cm

Figure 14. Tests 1 and 2, Recovery = 167 KC, Damped with 14 Ohms.

#3a



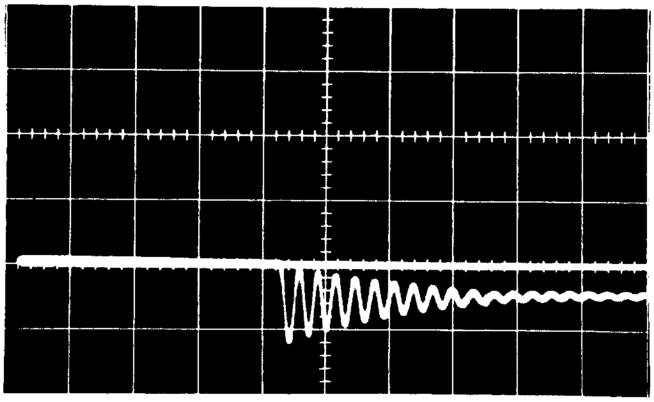
1700A/cm

2000V/cm

0.5ms/cm

CONTACT PART
INDICATION

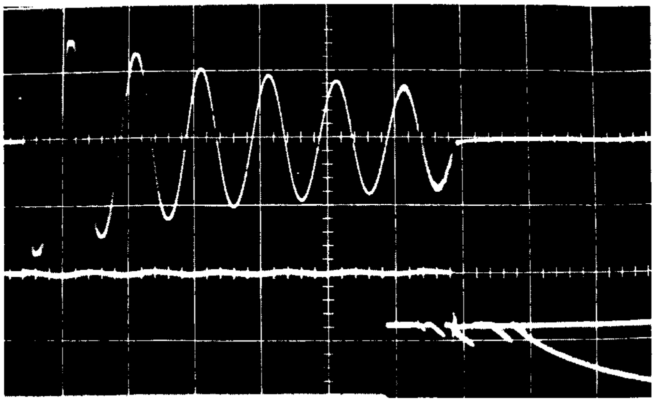
#3b



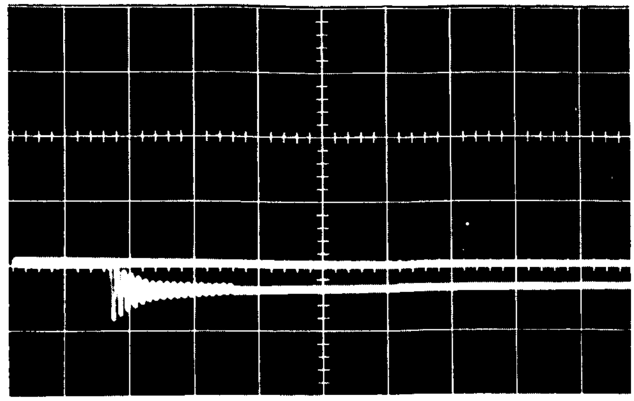
5000V/cm

20μs/cm

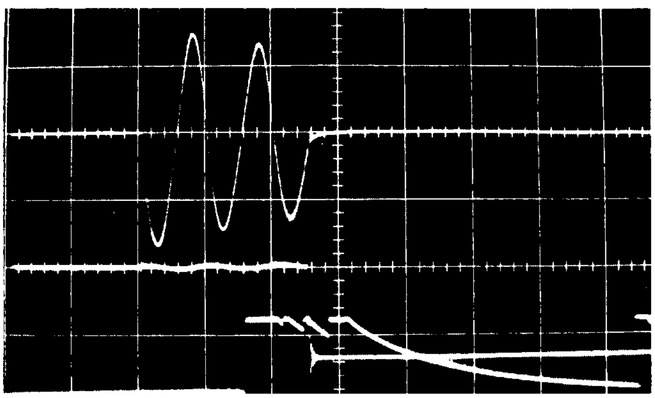
Figure 15. Test 3, Recovery Frequency = 167 KC, No Intentional Damping.



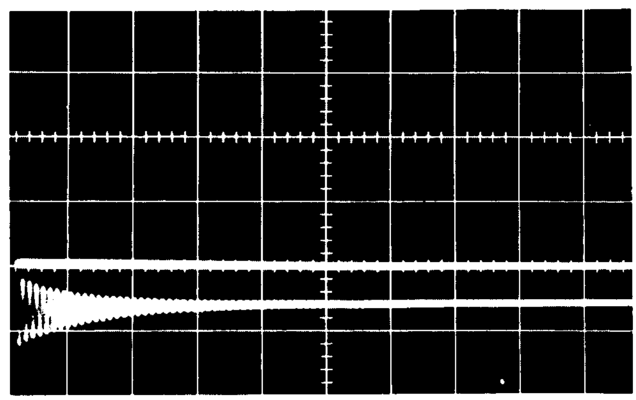
#4a



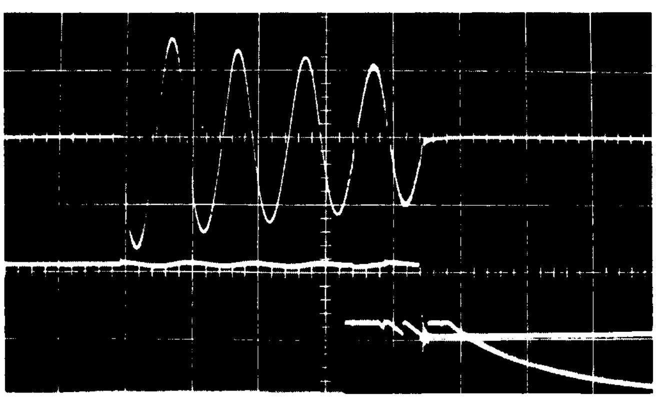
#4b 5000V/cm, 20μs/cm



#5a

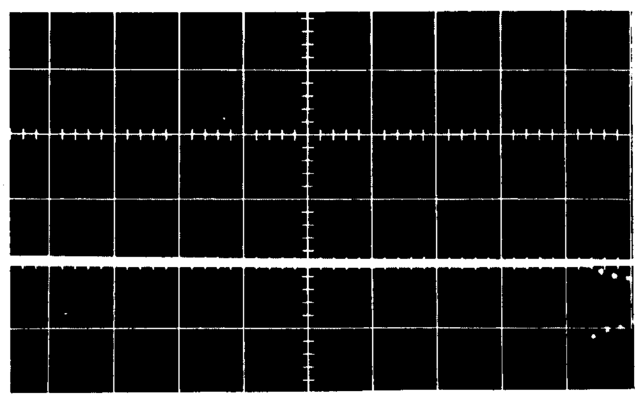


#5b 5000V/cm, 20μs/cm



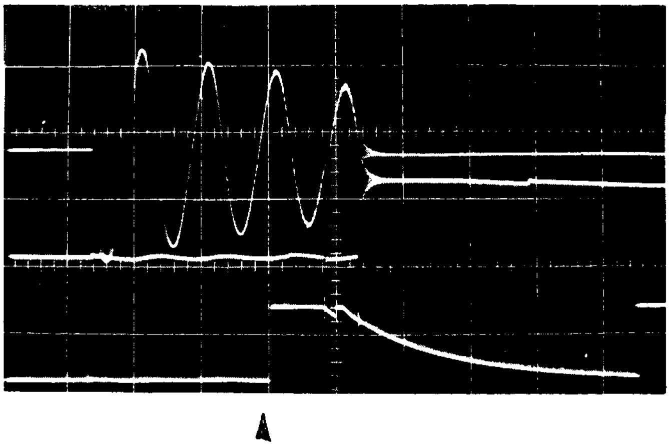
#6a CONTACT PART INDICATION

1700A/cm
2000V/cm
0.5ms/cm

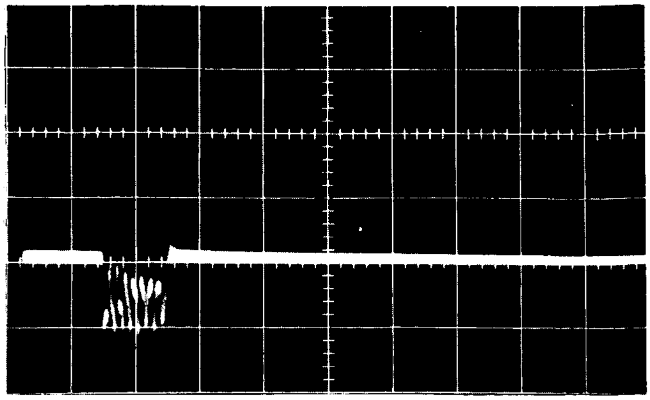


#6b 5000V/cm, 10μs/cm

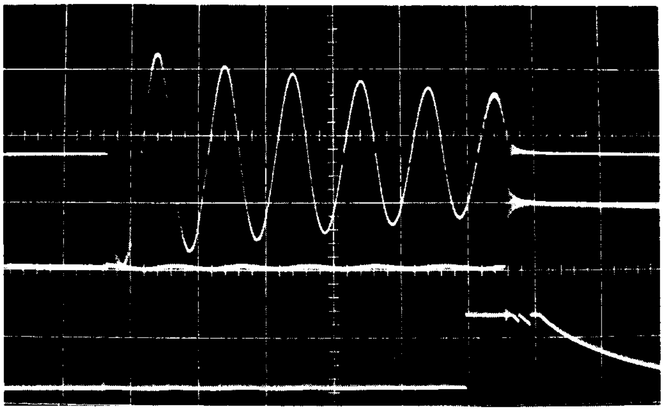
Figure 16. Tests 4, 5 and 6, Recovery Frequency = 460 KC.



#7a CONTACT PART INDICATION



#7b 5000V/cm
10μs/cm
(Voltage at a current zero before final interruption)



#8a 1700A/cm
2000V/cm
0.5ms/cm

Figure 17. Tests 7 and 8, Recovery Frequency = 780 KC.

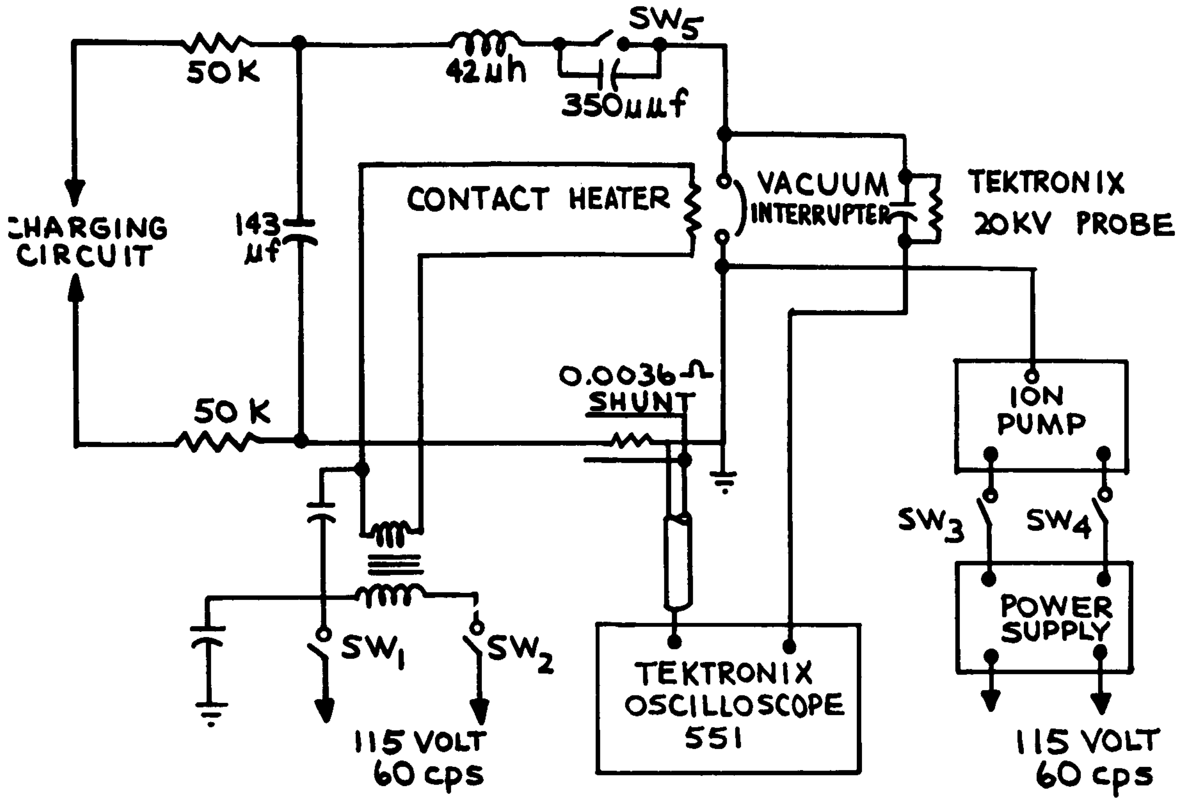
b. Interruption at full environment. The evaluation test at the heat sink temperature of 1000°F (538°C) were also conducted in the General Electric Switchgear Laboratory in Philadelphia. These tests were performed with the contact material test apparatus described in Section III-1 and shown in Fig. 4.

The ceramic vacuum chamber differs significantly from a prototype vacuum interrupter. Specifically the tantalum heater surrounding the contacts will act like a shield, however, it was not designed to be a good shield. In a prototype unit the arc shield would not be as close to the contacts and it would not be at 1500°C temperature, factors that were considered to limit performance.

The schematic circuit diagram is shown in Figure 18. The main storage capacitor was adjusted to 143 microfarads and was tuned by the current limiting choke of 42 microhenries to produce a 2000 cps discharge frequency. The bank was charged to 2200 volts for the final six interruption tests at 640°C contact temperature.

During the charging and standby period the ion pump on the test chamber was energized through SW_3 and SW_4 and the contact heater was energized through SW_1 and SW_2 so that the high vacuum, high temperature conditions were maintained in the test chamber. During an interruption test these switches were opened to prevent spurious grounding paths and possible damage to test apparatus.

The switches SW 1, 2, 3, and 4 were opened before SW_5 was closed to establish current. The test current was allowed to flow for 16 milliseconds before the vacuum interrupter contacts were parted. The cathode ray oscilloscope (CRO) was triggered approximately 4 milliseconds before contact



PRESSURE AND TEMPERATURE STABILITY

- RELAYS INSURE POWER ON PUMPS & HEATER MOST OF TIME
- PRESSURE CHANGE FROM 10^{-7} TO 10^{-6} TORR RANGE DURING SHOT
- TEMPERATURE CHANGE LESS THAN 50° DURING SHOT

Figure 18. AC Interruptor Test Evaluation.

parting. An auxiliary control network, not shown in the circuit diagram, was used to automatically provide the proper sequence. The ion pump and contact heater power was off for approximately 1 second. During this time the temperature of the contacts would decrease 15°C, by measurement, from 650°C and the pressure in the chamber changed from 1×10^{-7} to less than 1×10^{-6} Torr. In the 20 millisecond period from the start of the test to arc extinguishing the pressure did not rise above 7.5×10^{-7} Torr and the contact temperature did not change more than 10°C.

This series of AC interruption tests were made after a series of DC tests. Therefore the contact conditioning procedure before the DC test is included here as it also preceded the AC test.

The system was pumped down at room temperature to a pressure of 4×10^{-6} Torr. The oven was assembled and the chamber was heated to 350°C in the oven. The ion pumps, bakeable valve and vacuum lines were out-gassed by a heat gun. Data on the bakeout is given in tabulation 5. After a total of 20 hours of which 17 were at 350°C the system was cooled and pumped down to 2×10^{-8} Torr. Pumping the system down at room temperature after a low temperature bakeout has been found helpful in reaching the 10^{-7} pressure region during the high temperature bakeout.

The data for the 600°C bakeout is listed as item 2 in tabulation 5. The duration of the bakeout was 44 hours with 36 hours at 600°C. The final pressure at the end of the bakeout was 7×10^{-7} Torr.

The next step in conditioning of the contacts was Hi-pot testing at room temperature, item 3, tabulation 5. The contacts were blocked in an open position with a 1/8 inch separation. Arc-over occurred once at 25 KV with

TABULATION 5

SYSTEM PREPARATION FOR INTERRUPTION TESTS

MOLYBDENUM CONTACTS

1. System Bake-out at 350°C

Date	Time	Hours		Temp. °C	Pressure Torr
7/24	10:50 a.m.			25	4×10^{-7}
	11:20			175	5×10^{-6}
	2:00 p.m.	21		275	2×10^{-5}
	3:00			330	1.5×10^{-5}
	6:30		17	350	6×10^{-6}
	7:30			350	3.5×10^{-6}
7/25	8:00 a.m.			350	6×10^{-7}

2. Vacuum Chamber Bake-out at 600°C

Date	Time	Hours		Temp. °C	Pressure Torr
7/25	4:10 p.m.			32	2×10^{-8}
	4:20	Contacts Closed			
	5:30			365	4.5×10^{-6}
	6:00			480	-
	11:50			530	2.5×10^{-6}
	12:00	44		560	-
7/26	12:10 a.m.			560	-
	10:20			560	1×10^{-6}
	12:00 Noon		36	610	-
	1:00 p.m.			620	-
	9:45			620	9×10^{-7}
7/27	8:50 a.m.			620	7×10^{-7}

During the 600°C bake-out of the vacuum chamber the ion pumps, the bakeable valve, and the interconnecting lines are cooled to approximately room temperature. The oven arrangement is shown in Figure 4. Room temperature air is blown through the tunnel under the oven bottom.

3. Hy-Pot Test

All heaters off and equipment down to room temperature.

Contacts separated 1/8 inch.

Break-down occurred at 25 KV, recovered and continued to hold off 25 KV without shut-down of hy-pot tester.

immediate recovery without shutting the test equipment off. Since the chamber continued to hold off 25 KV and 28 KV was the surface arc-over voltage on the outside of the chamber, further conditioning could not be accomplished.

The AC interruption tests were made at 480 and 640°C contact temperature. The pressure in the vacuum chamber was less than 7.5×10^{-7} during all the tests. The maximum current interrupted was 4300 amperes crest at 2000 volts crest 2000 cps. Figures 19, 20, and 21 are representative oscillograms made during the tests. Detailed test data are included in Tabulation 6.

2. DC Interruption Evaluation

The DC contactor evaluation tests were also conducted in the Switchgear Laboratory. The circuit in Figure 18 was modified by replacing the current limiting reactor by a 500 ohm resistor. The main capacitor bank was increased to 250 microfarads. (See Figure 23). The contact materials test equipment was again used for the DC evaluation, as seen in Figure 22.

The test procedure was the same as for the AC interruption tests. The contact heater and ion pump were de-energized in the manner described for the AC test. The capacitor bank, however, was charged to 11-13 KV which was high enough to insure a residual of 10 KV for full scale clearance test. There was a small decay in the DC current as the 250 microfarad capacitor discharged before contact part and interruption. This decay was well under 30% in all test cases as can be seen by the oscillograms in Figures 24 thru 27.

As in the AC tests the contact temperature change was less than 10°C at 650°C and the pressure rise was from 1×10^{-7} to 7.5×10^{-7} Torr. Both changes were due to the interruption of power to the contact heaters and ion pump during a test.

TABULATION 6

AC INTERRUPTION TEST

MOLYBDENUM CONTACTS

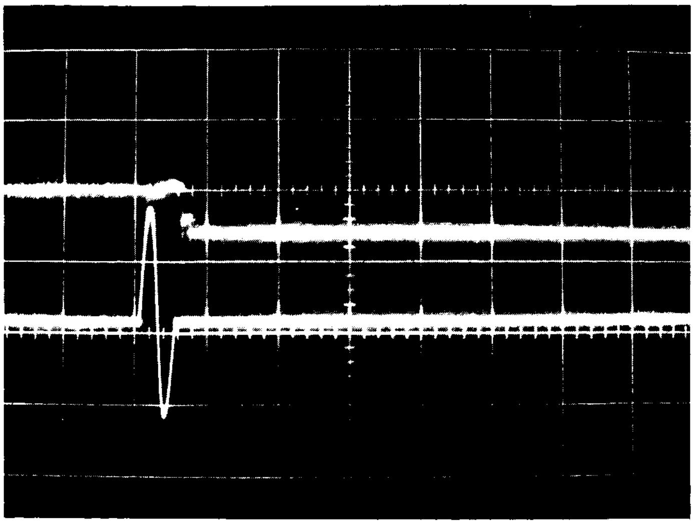
VACUUM CHAMBER PRESSURE LESS THAN 7.5 x 10^{-7} mm of Hg
FOR ALL TESTS

Test #	Cap. Bank Initial Charge Volts	Interruption Amps Crest Value	Temp °C	Remarks
53	500	165	480	-
54	500	280	480	-
55	500	750	480	320V steady-state recovery voltage
56	500	660	480	250V steady-state recovery voltage
57	500	500	480	200V steady-state recovery voltage
58	1000	1000	480	500V steady-state recovery voltage
59	1000	1600	480	probe measured voltage across inductor plus vacuum interrupter to check response
60	1000	1400	480	700V steady-state recovery voltage
61	1000	1650	480	750V steady-state recovery voltage
62	1500	500	480	cleared late due to poor timing
62A	1500	2200***	640	1200V steady-state recovery voltage - restruck after 0.3 millisecond - cleared restrike of approx. 2000 amps crest
63	1500	3000***	640	cleared first loop - 1400V steady-state recovery voltage
64	1700	1400	640	timing poor

***Surpass contract specification

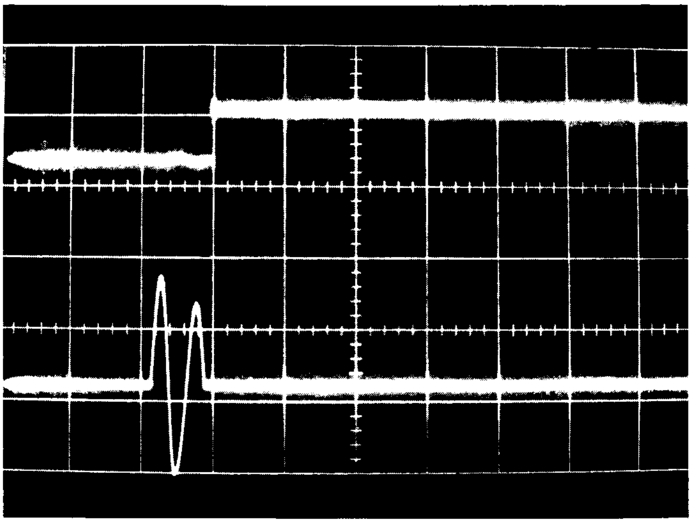
Test #	Cap. Bank Initial Charge Volts	Interruption Amps Crest Value	Temp ^{o}C	Remarks
65	2000	1800***	640	timing poor
66	2200	1400***	640	timing poor
67	2200	1400	640	timing poor
68	2200	2500***	640	-
69	2200	1100	640	timing poor
70	2200	900	640	timing poor
71	2200	4300***	640	cleared first loop with 2000V steady-state recovery voltage

***Surpass contract specification



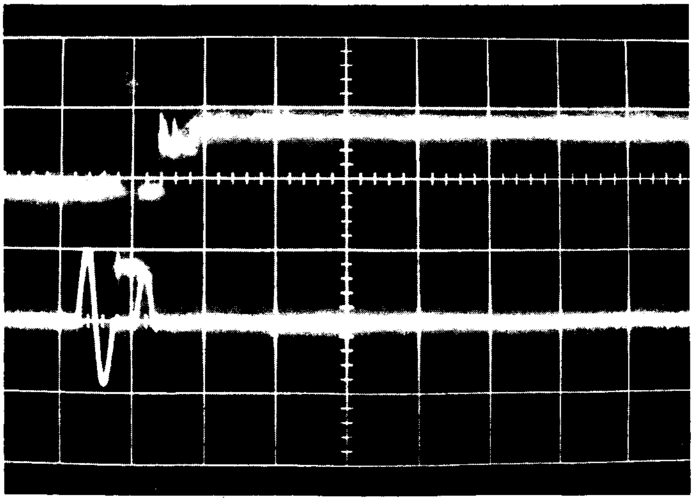
Test No. 55

Top Trace - Voltage 500 V/cm
Bottom Trace - Current 555 a/cm
Time Scale - 1 millisec/cm
Temperature - 480 C
Pressure - 7 x 10^{-8} MM of Hg



Test No. 61

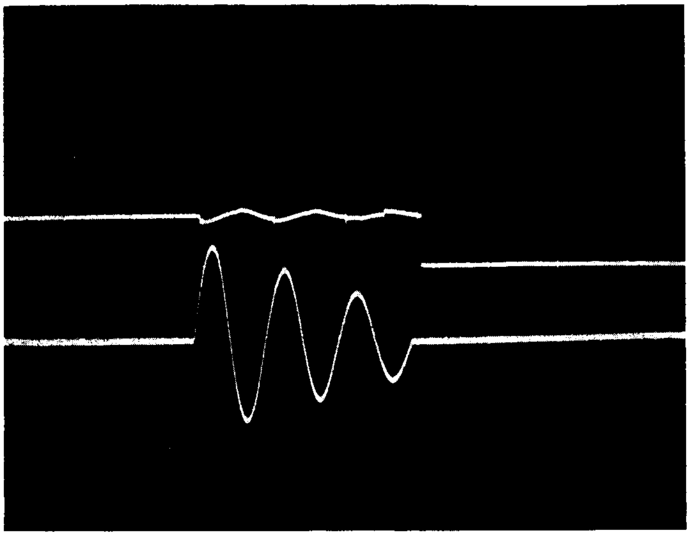
Top Trace - Voltage 1000 V/cm
Bottom Trace - Current 1380 a/cm
Time Scale - 1 millisec/cm
Temperature - 480 C
Pressure - 7 x 10^{-8} MM of Hg



Test No. 62A

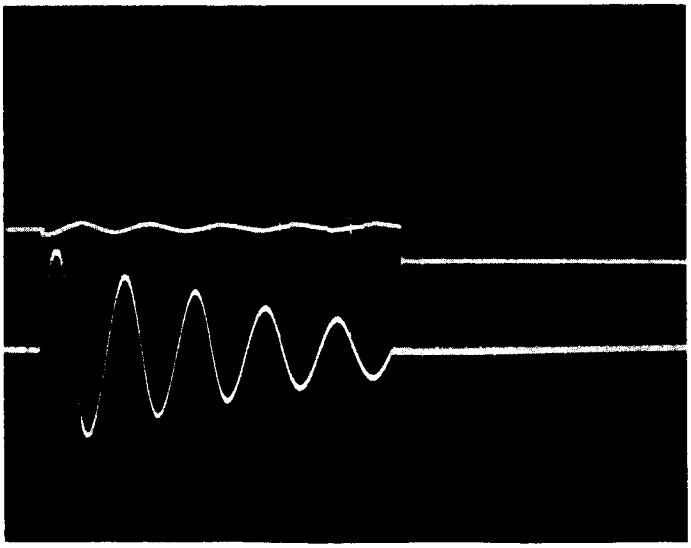
Top Trace - Voltage 1000 V/cm
Bottom Trace - Current 2760 a/cm
Time Scale - 1 millisec/cm
Temperature - 640 C
Pressure - 6 x 10^{-7} MM of Hg

Figure 19. AC Interruption Tests 55, 61 and 62A.



<u>Test No. 65</u>

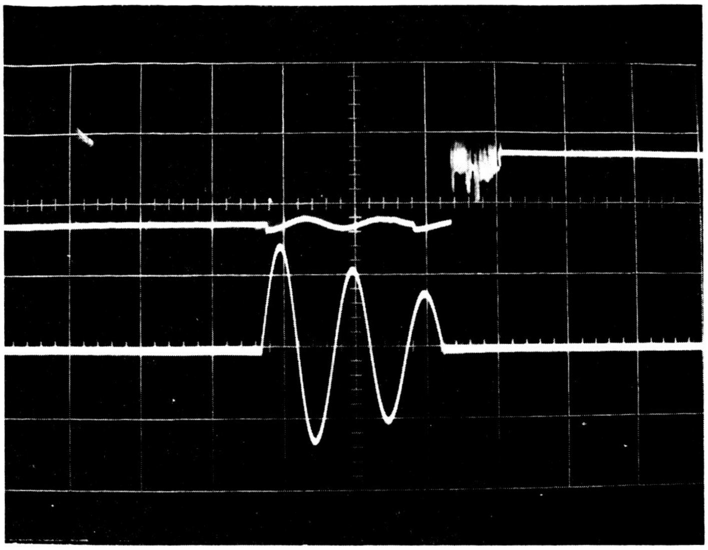
Top Trace - Voltage 1000 V/cm
Bottom Trace - Current 2760 a/cm
Time Scale - 0.5 millisec/cm
Temperature - 640 C
Pressure - 5 x 10^{-7} MM of HG



<u>Test No. 66</u>

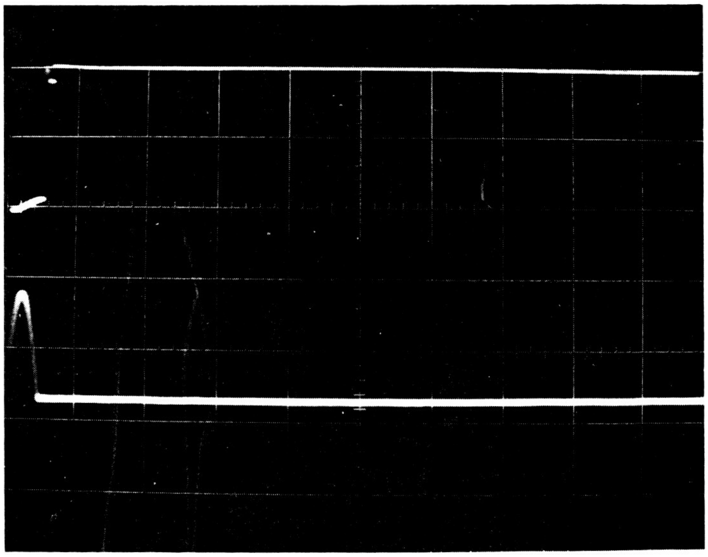
Top Trace - Voltage 1000 V/cm
Bottom Trace - Current 2760 a/cm
Time Scale - 0.5 millisec/cm
Temperature - 640 C
Pressure - 6 x 10^{-7} MM of Hg

Figure 20. AC Interruption Tests 65 and 66.



Test No. 68

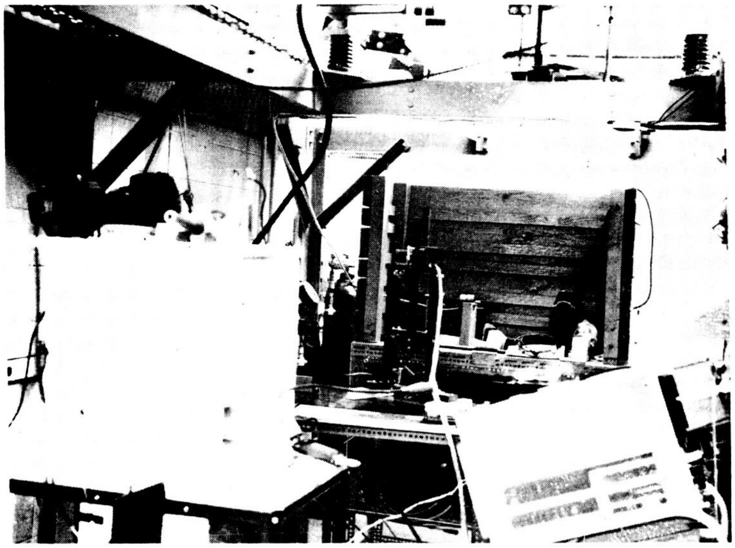
Top Trace - Voltage 1000 V/cm
Bottom Trace - Current 2760 a/cm
Time Scale - 0.5 millisec/cm
Temperature - 640 C
Pressure - 5 x 10^{-7} MM of Hg



Test No. 71

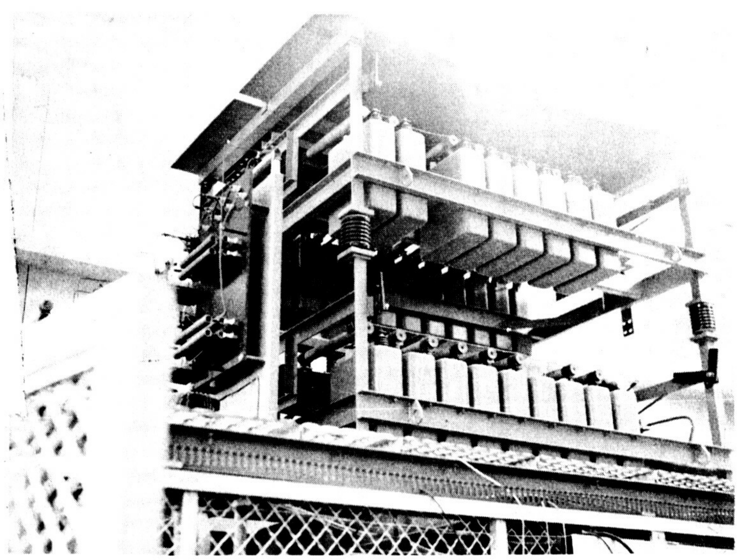
Top Trace - Voltage 1000 V/cm
Bottom Trace - Current 2760 a/cm
Time Scale - 0.5 millisec/cm
Temperature - 640 C
Pressure - 5 x 10^{-7} MM of Hg

Figure 21. AC Interruption Tests 68 and 71.



A. General View of Test Area

Oven Containing Vacuum Interrupter is at left foreground - Closing switch in center - Oscilloscope at right foreground.



B. Capacitor Bank and Charging Circuit Used for Tests on Vacuum Interrupter.

Figure 22. Interruption Test Equipment.

These tests were conducted with tungsten contacts vacuum processed and brazed as described in section III-B-1. The contacts were not preconditioned in the vacuum capsule at high temperature as described in that section. The data for the 13 interruption tests are listed in tabulation 7. Oscillograms of eleven of the tests are shown in Figures 24 thru 27. The difficulties encountered were attributed to the following problem:

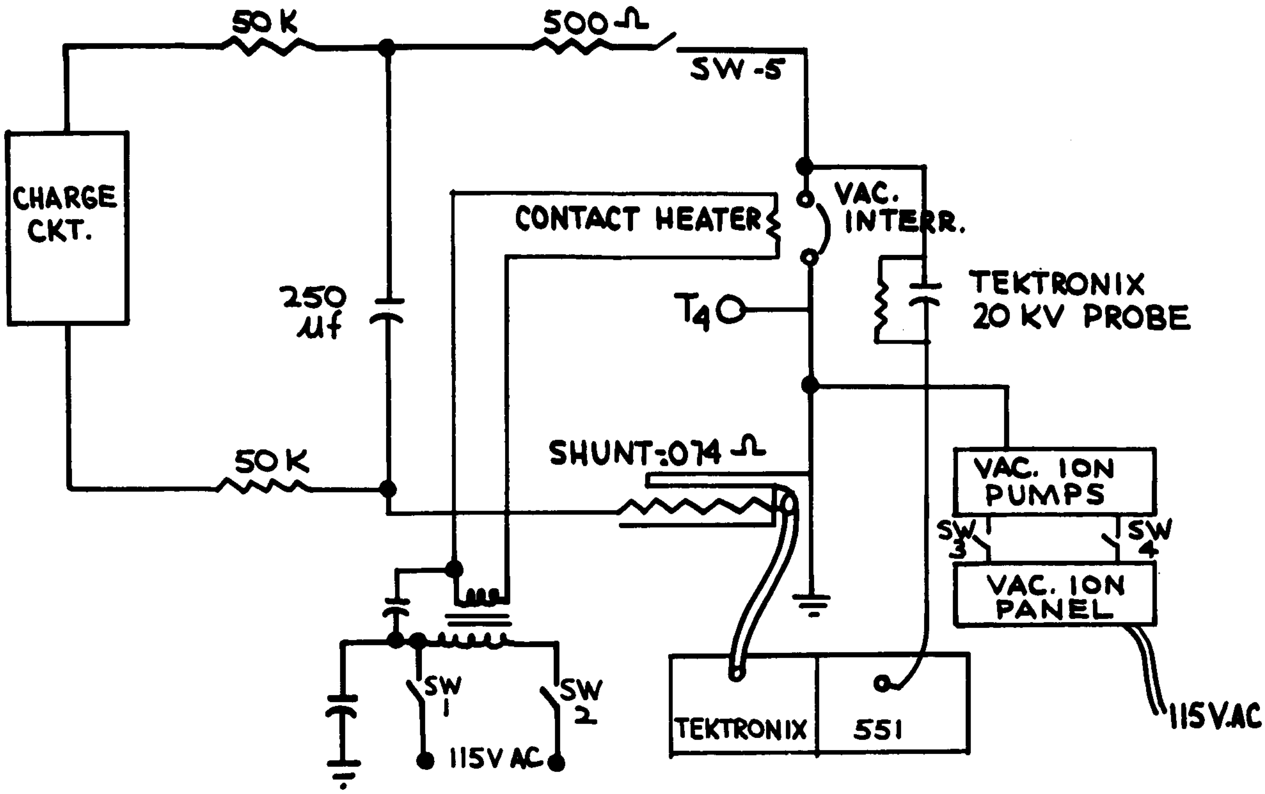
- Contacts were not preconditioned in the vacuum capsule at the high temperature.
- Failure of the support of the contact heater.

The DC interruption tests were continued after installing a new tantalum contact heater, cleaning and desorbing the components of the vacuum capsule, and installing new molybdenum contact tips. The material of the tips was changed to provide a comparison with the tungsten test data.

The new molybdenum contact tips were preconditioned as described in section III-B-1,AC Interruption Evaluation.

A total of 14 interruption tests were made at room temperature, 14 with the contacts at 200°C, 5 at 420°C, and 11 at a contact temperature of 640°C. The pressure in the vacuum chamber was less than 7.5×10^{-7} Torr for all tests. The data is given in Tabulation 8 and oscillograms of 9 of the tests are included in Figures 28 thru 30.

The results of the AC and DC interruption tests indicate that the contact specifications for the AC Circuit Breaker and DC Engine Contactor can be met by a vacuum contactor with molybdenum contacts 3/4 inch in diameter with a contact separation of 1/4 inch. The difficulties encountered in the first series of DC interruption tests with tungsten contacts should be attributed to the failure of the contact heater and the lack of preconditioning of the contacts and not to the tungsten material of the contacts.



D.C. CURRENT STABILITY DURING TEST

- DECAY OF D.C. CURRENT WELL UNDER 30% IN ALL CASES
- IMPROVEMENTS IN D.C. LEVEL AT TRIP WITH BETTER TIMING

Figure 23. DC Contactor Test Evaluation.

TABULATION 7

DC INTERRUPTION TEST

TUNGSTEN CONTACTS

VACUUM CHAMBER PRESSURE LESS THAN 7.5 x 10^{-7} Torr
FOR ALL TESTS

Test #	Test KV	Test Amps	Contact Temp °C	Approx. Arc Duration M Sec	Remarks
1	-	-	640		(CRO) did not trigger thermocouple arced to ground
2	3 Residual	-	645	45	Interrupter did not clear. arcing in oven
3	4	8.1	643	140	Cleared
	4			28	Held voltage. arcing in oven
4	4	6.5	645	180	Cleared Arcing in oven

Oven opened all thermocouples except #4 on lower contact.

Test #	Test KV	Test Amps	Contact Temp °C	Approx. Arc Duration M Sec	Remarks
5	-	19	646	16	Cleared then broke down.
	2 Residual				Final clearing
6	10	19	645	20	Cleared momentarily
	7	12.1		90	Final clearing
7	10	9	643	-	First of 5 clearings Arcing in oven
8	10	20	640	4	Cleared
				130	Held then broke down. Arcing in oven
9	-	-		-	(CRO) did not trigger
10	4.5 Residual		645		Did not clear. Evidence of Arc in air on CRO.

Hi-pot test made. Switch initially withstood 6 KV DC and decreased to 2 KV.

Cooled to room temperature for inspection. Signs of arcing on lower Kovar ring and and on lower vacuum flange.

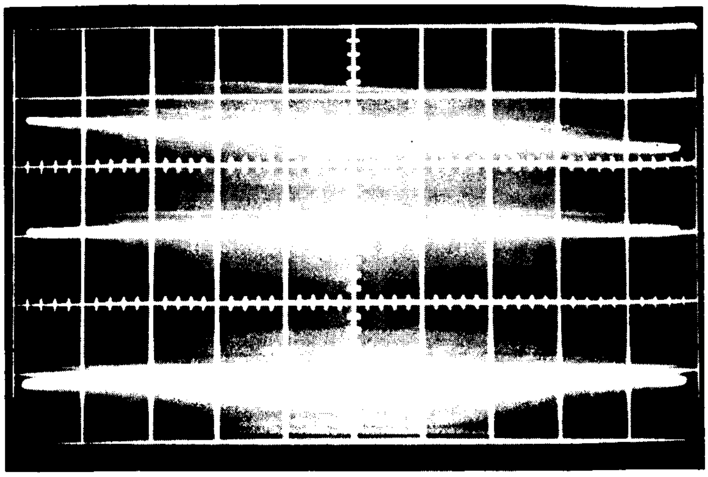
Switch broke down at 25 KV DC Hi-pot

Test #	Test KV	Test Amps	Contact Temp °C	Approx. Arc Duration M Sec	Remarks
11	9	18	Room	34	Cleared. Held until bank intentionally discharged
12	9	18	Room	26	Cleared as above
13	10.5	20.5	Room	28	Cleared as above

Vacuum chamber opened for inspection.

Contact heater broken loose from top mounting.

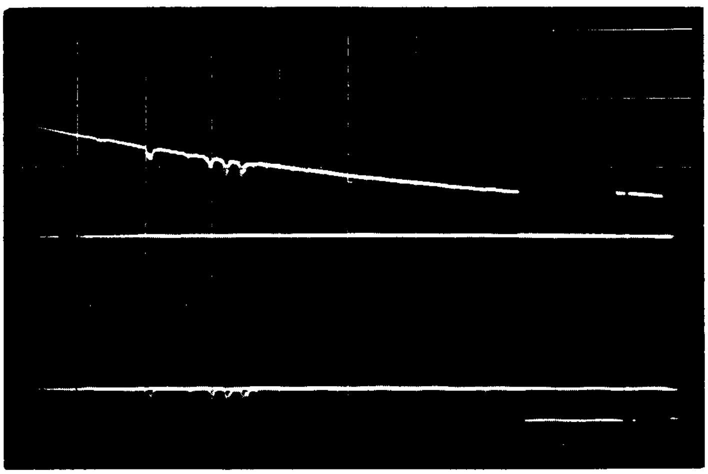
Test discontinued.



Test #2 - Top trace -
current - 13.5 amps/div.

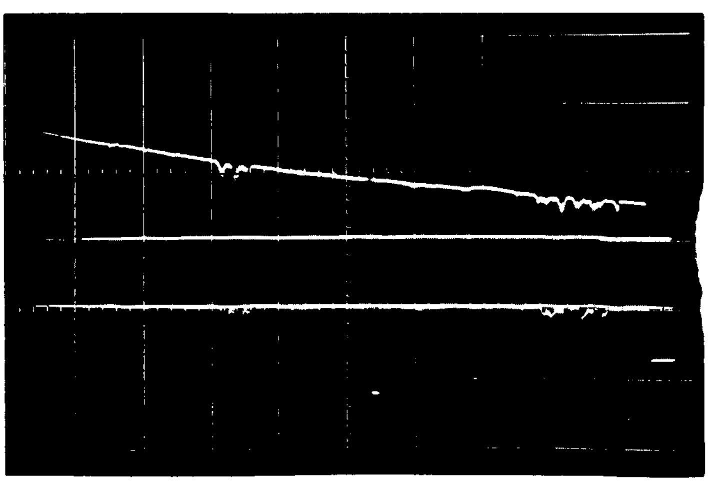
Bottom trace -
Voltage - 10 kv/div.

Time Scale - 5 msec./div.



Test #3 - Top trace -
Current - 13.5 a/div.

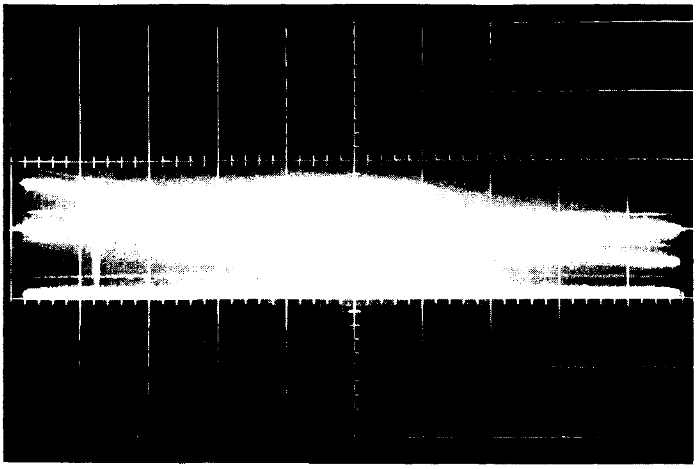
Bottom trace -
Voltage - 10 KV/div.
Time Scale - 20 msec./div.



Test #4 - Top trace -
Current - 13.5 a/div.

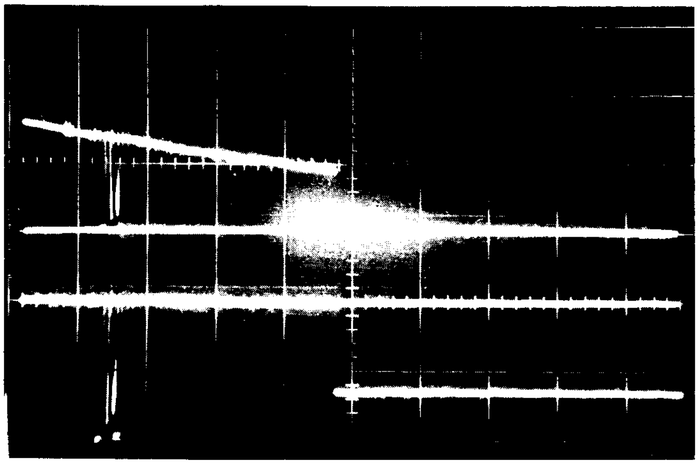
Bottom trace -
Voltage 5 KV/div.
Time Scale - 20 msec./div.

Figure 24. Tungsten DC Interruption Tests 2, 3 and 4.

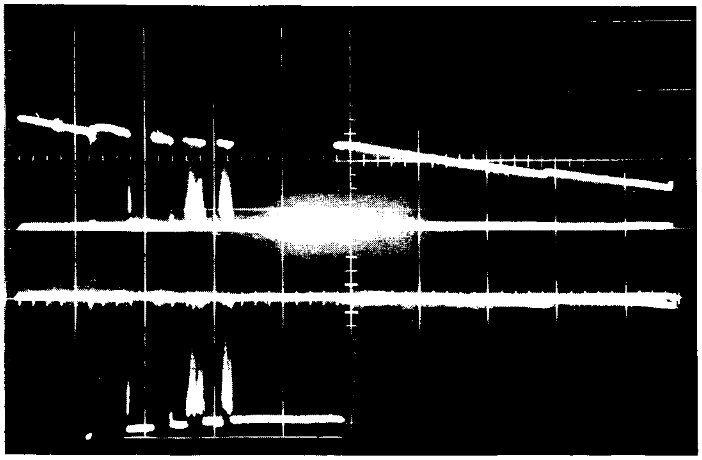


Test #5 - Top trace -
Voltage 5 KV/div.

Bottom trace - current
13.5 a/div.
Time Scale - 20 msec./div.

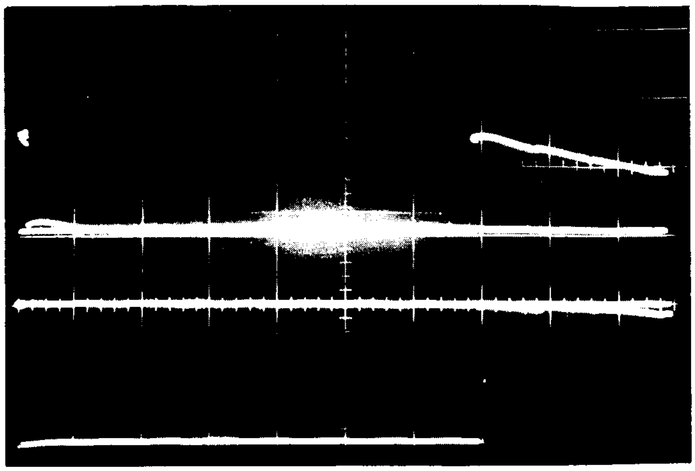


Test #6 - Top Trace
Current - 13.5 a/div.
Bottom trace - voltage
5 KV/div.
Time Scale - 20 msec./div.

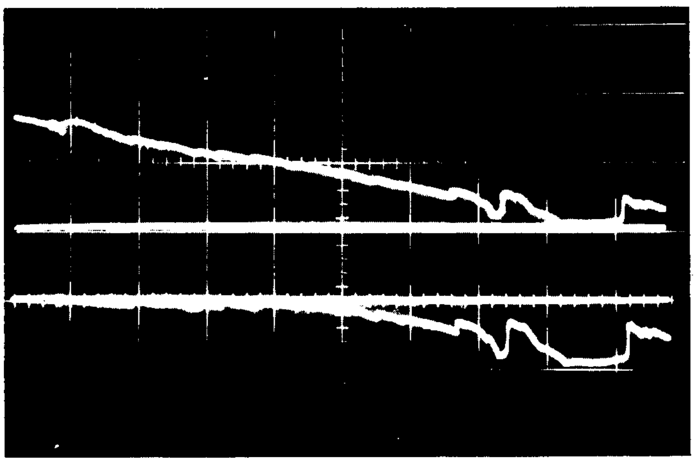


Test #7 - Top Trace
Current - 13.5 a/div.
Bottom trace - Voltage
5 KV/div.
Time Scale - 20 msec./div.

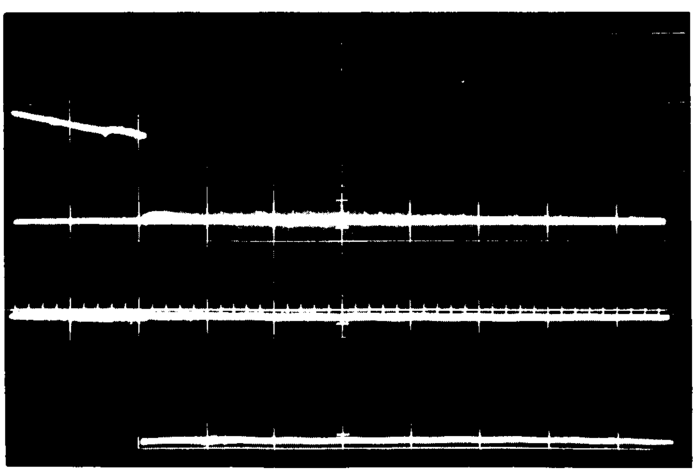
Figure 25. Tungsten DC Interruption Tests 5, 6 and 7.



Test #8 - Top Trace
Current - 13.5 a/div.
Bottom Trace - Voltage
5 KV/div.
Time Scale - 20 msec./div.

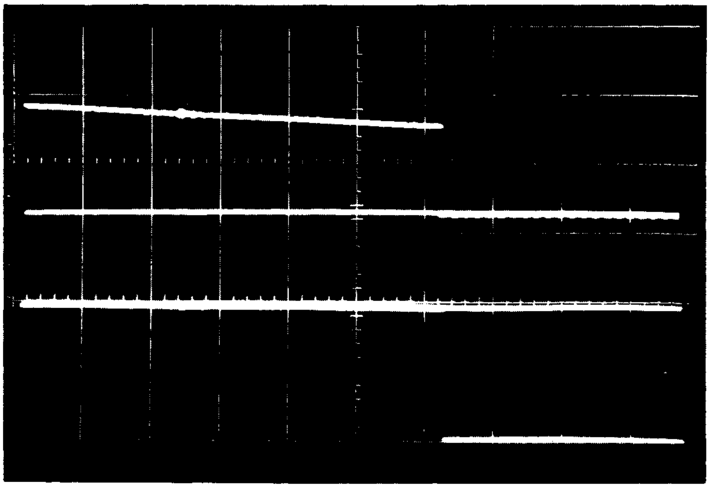


Test #10 - Top Trace
Current - 13/5 a/div.
Bottom trace - Voltage
5 KV/div.
Time Scale - 20 msec./div.

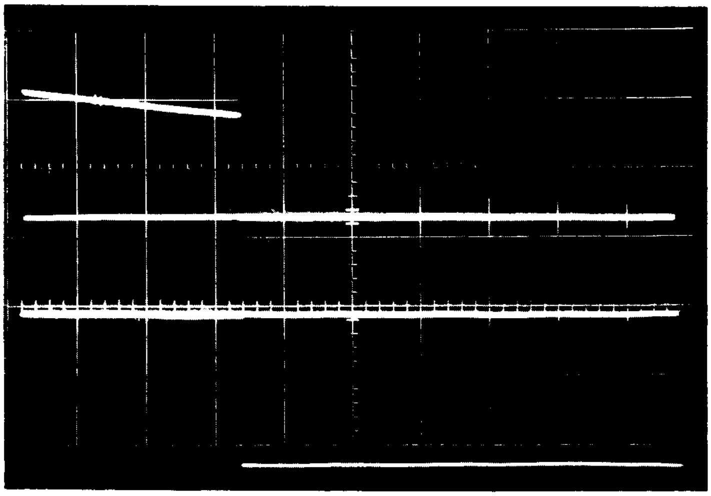


Test #11 - Top Trace -
Current - 13/5 a/div.
Bottom Trace - Voltage
5 KV/div.
Time Scale - 20 msec./div.

Figure 26. Tungsten DC Interruption Tests 8, 10 and 11.



Test #12 - Top Trace
Current - 13.5 a/div.
Bottom Trace - Voltage
5 KV/div.
Time Scale - 5 msec./div.



Test #13 - Top Trace
Current - 13.5 a/div.
Bottom Trace - Voltage
5 KV/div.
Time Scale - 10 msec./div.

Figure 27. Tungsten DC Interruption Tests 12 and 13.

TABULATION 8

DC INTERRUPTION TESTS

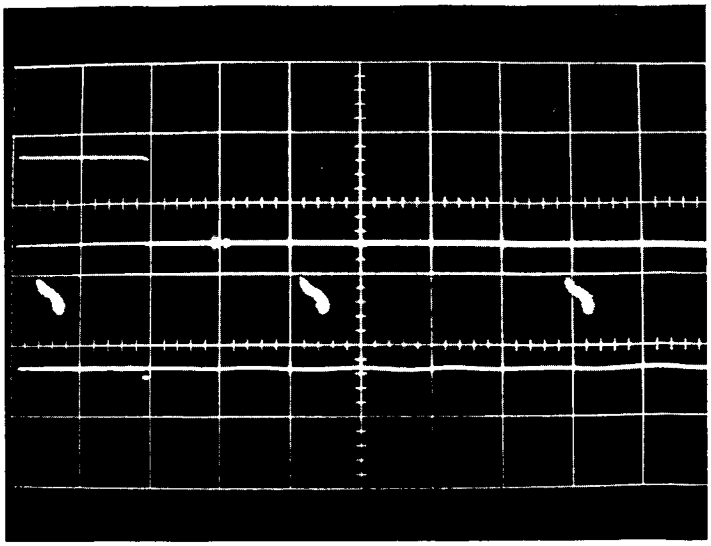
MOLYBDENUM CONTACTS

VACUUM CHAMBER PRESSURE LESS THAN 7.5 x 10^{-7} Torr
FOR ALL TESTS

Test #	Test KV	Test I	Temp (^oC)	Approx. Arc During (MSec)	Remarks
1	2	4	room	0.5	CRO shows Arc Rec. voltage off film
2	"	"	"	0.5	Cleared
3	3.6	7.5	"	2.0	"
4	5.5	11.5	"	2.0	"
5	6.5	13.0	"	23	"
6	7.0	14.0	"	10	"
7	6.5	13.5	"	17	"
8	8.8	17.0	"	3	"
9	9.0	18.0	"	5	"
10	9.5	20.0	"	6	"
11	9.5	20.0	"	8	"
12	8.5	18.0	"	27	"
13	9.0	19.5	"	12	"
14	9.5	20.0	"	11	"
15	4.8	9.5	200	1	"
16	4.8	9.5	"	36	"
17	8.5	17.5	"	36	"
18	8.5	17.5	"	16	"
19	9.0	19.0	"	40	Clearing not shown on CRO - Cleared

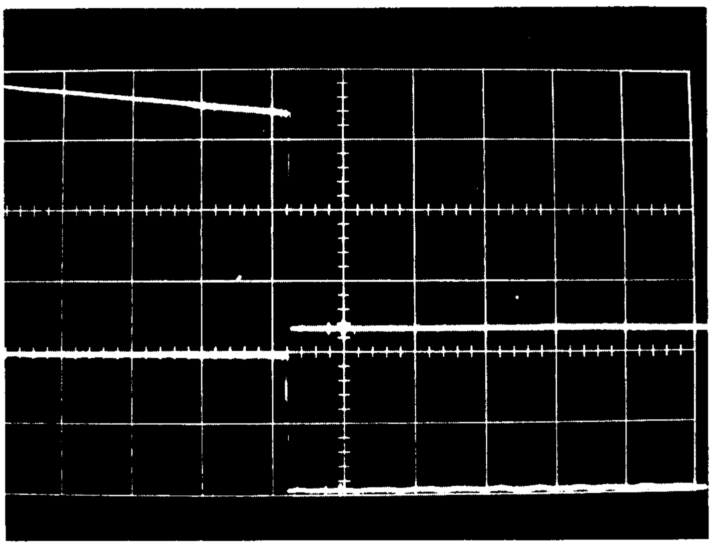
Test #	Test KV	Test I	Temp (^oC)	Approx. Arc During (MSec)	Remarks
20	-	-	200	40	Approx. 8500V - 17 a as shown by residual charge left on cap. bank
21	9.0	19.0	"	19	Cleared
22	9.8	19.5	"	15	"
23	8.5	17.5	"	24	"
24	9.8	19.5	"	8	"
25	9.0	17.5	"	22	"
26	9.8	19.5	"	9	"
27	8.0	17.0	"	27	"
28	9.8	19.5	"	14	"
29	4.8	9.0	420	3	"
30	9.8	19.5	"	5	"
31	9.5	19.5	"	10	"
32	9.0	18.0	"	17	"
33	9.8	19.5	"	11	"
34	4.8	9.0	640	4	"
35	9.5	19.0	"	12	"
36	9.8	19.5	"	13	"
37	9.5	19.0	"	24	"
38	10.0	20.0***	"	12	"
39	10.5	21.0***	"	14	"
40	9.0	18.0	"	29	"
41	9.8	19.5	"	26	"
42	10.8	21.0	"	3	"
43	10.0	20.0***	"	11	"
44	10.8	21.0***	"	7	"

*** Surpass contract specifications.



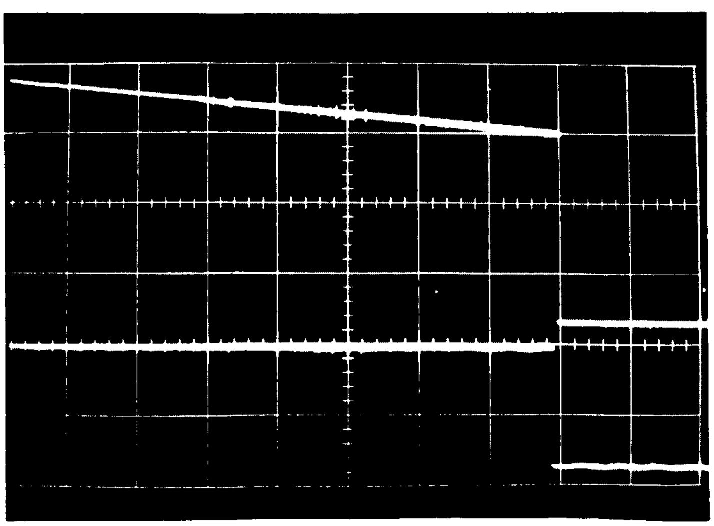
Test No. 1

Top Trace - Current 2.7 a/cm
Bottom Trace - Voltage 100 V/cm
Sweep Speed - 5 millisec/cm
Temperature - 25 C
Pressure - Less than 1 x 10^{-9} MM of Hg



Test No. 11

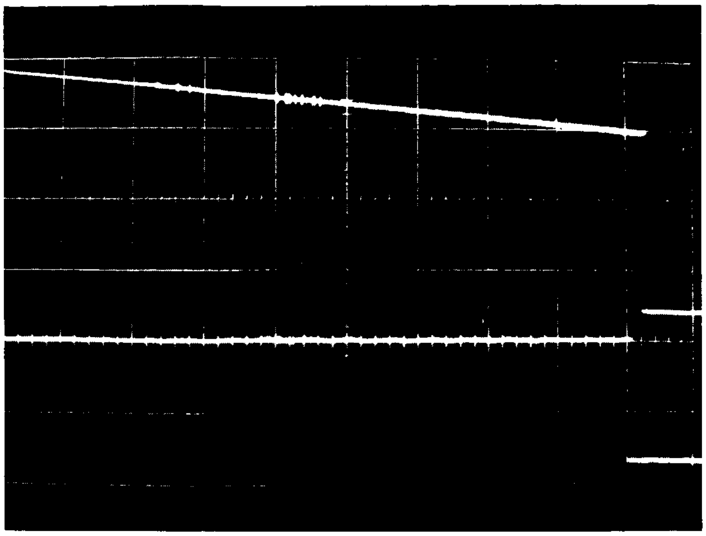
Top Trace - Curr. 6.75 a/cm
Bottom Trace - Voltage 5000 V/cm
Sweep Speed - 5 millisec/cm
Temperature - 25 C
Pressure - Less than 1 x 10^{-9} MM of Hg



Test No. 12

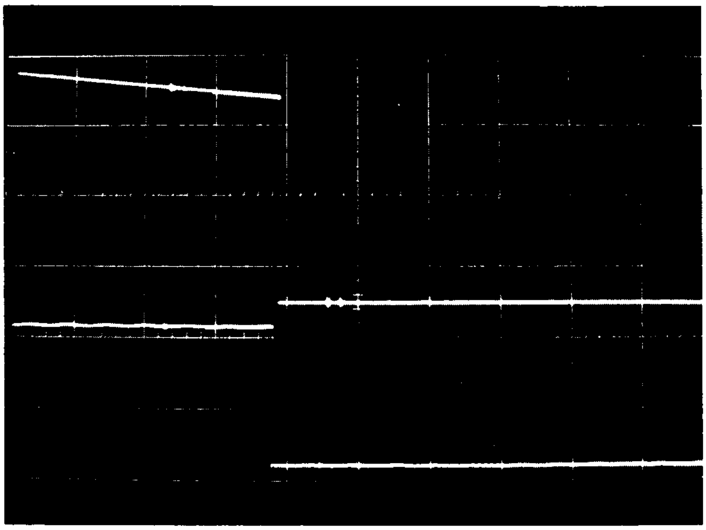
Top Trace - Curr. 6.75 a/cm
Bottom Trace - Voltage 5000 V/cm
Sweep Speed - 5 millisec/cm
Temperature - 25 C
Pressure - Less than 1 x 10^{-9} MM of Hg

Figure 28. Molybdenum DC Interruption Tests 1, 11 and 12.



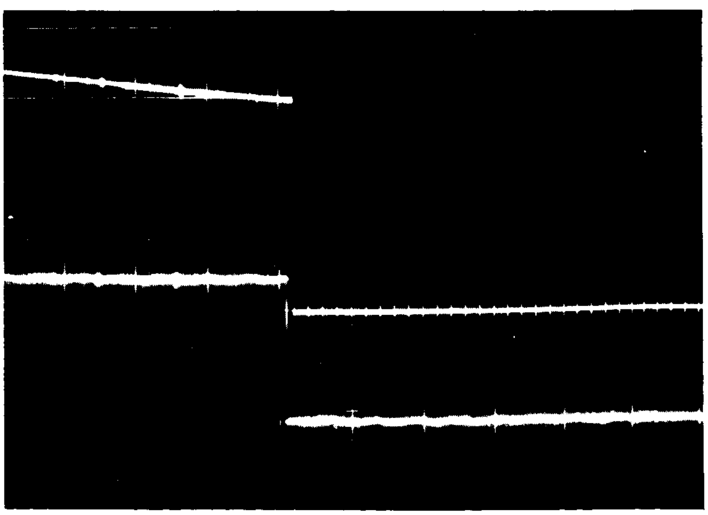
Test No. 17

Top Trace - Curr. 6.75 a/cm
Bottom Trace - Voltage 5000 V/cm
Sweep Speed - 5 millisec/cm
Temperature - 200 C
Pressure - 1 x 10^{-9} MM of Hg



Test No. 24

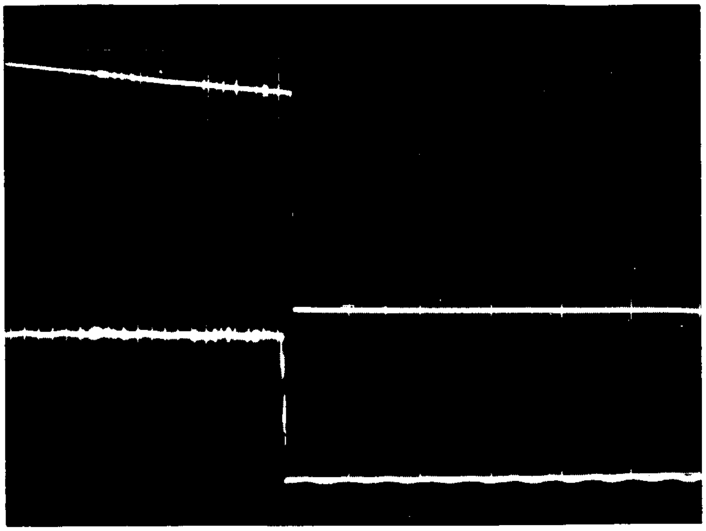
Calibration Same as No. 17
Temperature - 200 C
Pressure - 1 x 10^{-9} MM of Hg



Test No. 38

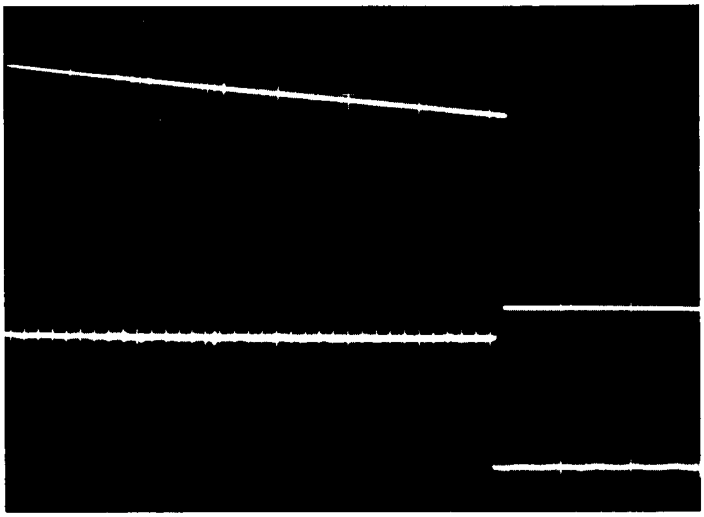
Calibration same as No. 17
Temperature - 640 C
Pressure - 5 x 10^{-7} MM of Hg

Figure 29. Molybdenum DC Interruption Tests 17, 24 and 38.



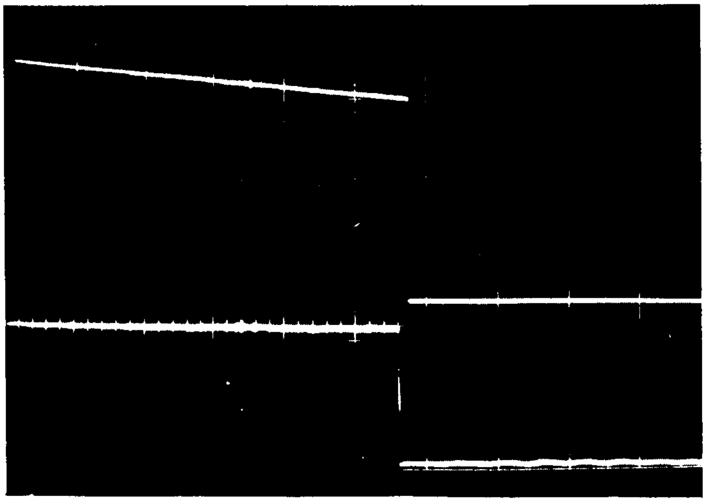
Test No. 39

Calibration same as No. 17
Temperature - 640 C
Pressure - 7.5 x 10^{-7} MM of Hg



Test No. 40

Calibration same as No. 17
Temperature - 640 C
Pressure - 7.5 x 10^{-7} MM of Hg



Test No. 41

Calibration same as No. 17
Temperature - 640 C
Pressure - 7.5 x 10^{-7} MM of Hg

Figure 30. Molybdenum DC Interruption Tests 39, 40 and 41.

IV CONCEPTUAL DESIGNS

A. AC Circuit Breaker

1. Summary

The literature survey and radiation study reported in Section II-A indicated that the 1000 volt, 3 phase, 600 ampere, 2000 cps AC Circuit Breaker should be a vacuum interrupter class of switchgear. The commercial use of this type of switchgear and the existance of technical background on arc interruption in a vacuum provided a broad base of technology for this device. The following general requirements were established for the breaker:

Contact diameter: 1 inch

Gap: 1/4 inch

Operating force: 50 lbs

Free travel of impact opening: 1/8 inch

Speed of travel at moment of contact: 40 inches/sec.

2. Vacuum Interrupter Design

Several design concepts have been studied for the AC vacuum interrupter for this environment. The culmination of these is shown in Figure 31.

The design of the vacuum switch must, of course, be predicated on its electrical insulation and arc interruption capabilities. The heat transfer characteristics of the electrode structure are equally critical under conditions of steady current flow. Finally, the welded structures and ceramic-metal seals involved in the vacuum design must assure durability.

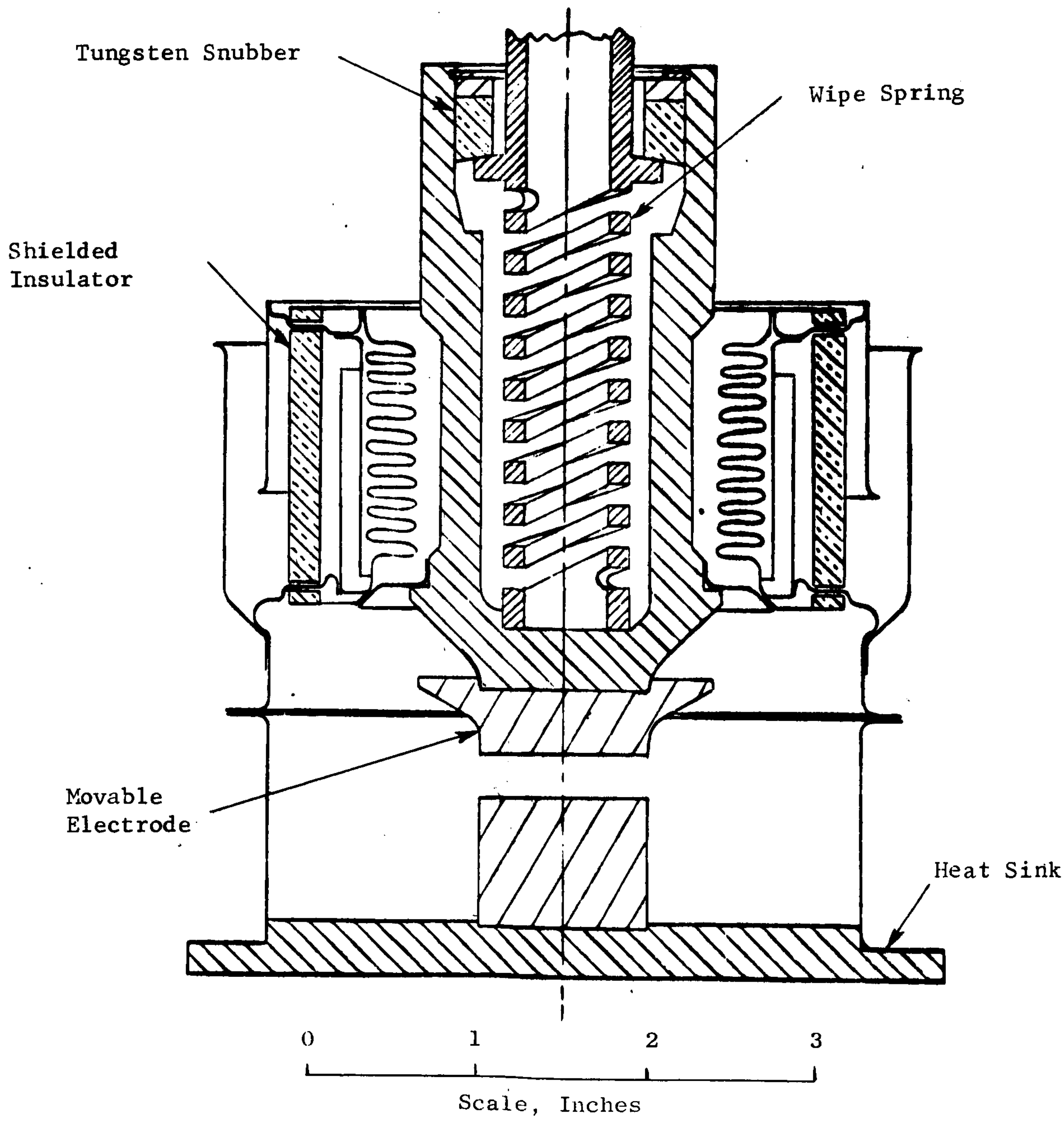


Figure 31. AC Vacuum Interrupter

An explanation of some of the features follows:

a. Heat Flow (Design and Material) - The majority of the heat is generated in the contact and is removed by a very short and direct conduction path of a large base area. The parts in this area where both heat conduction and electrical conduction are of prime importance, must have--in the operating environment, mainly temperature (1000°F = 538°C) limited characteristics of

- good electrical conductivity
- good thermal conductivity
- high melt temperature (for high-temperature furnace brazing)
- good brazability
- low vapor pressure
- good corrosion resistance at 550°C (for testing at temperature on earth) among many other easier to come by properties.

Both tungsten and molybdenum[22] have better electrical and thermal properties than nickel but the first is very hard to machine and the second corrodes significantly above 300°C in air. Niobium and tantalum have thermal and electrical properties about equal to nickel and melt temperatures higher than nickel, however, their behavior at 500°C in atmosphere is not as good as nickel. Copper is unsuitable because of high electrical resistivity at 500°C and a low melting temperature to say nothing of corrosion at the higher temperatures.

Since it is almost impossible to get good heat conduction both ways from the contact area the interrupter is designed to carry all the heat out thru one short direct route leaving the other electrode free of this consideration.

b. Ceramic-to-metal Seal - The ceramic-to-metal seal shown is of the active alloy "compensated" type which resists chemical attack much better than the metallized type. The hazard of chemical corrosion and its mode of attack has not been well defined. A nickel-ceramic seal for the environment and life can be made. Seals exceeding the temperature requirement have been made but not tested to anywhere near 20,000 hrs.[23]

c. Bake-out and Arcing Vaporization Shield - This shield is to keep the ceramic insulator from being coated by a conducting layer of metal molecules during high temperature bake-out. It also assists in extinguishing interruption arc by absorption of the arc vapor.

d. Cesium Vapor Shield - This shield is to prevent the ceramic insulator from being coated with migrating cesium from the engines. Whether this shield is really necessary or whether the one shown in the sketch is adequate is at present an unresolved consideration.

e. Contact Wipe Spring - The caged spring, Figure 31, serves as the over-travel or wipe spring providing a controlled contact force, provides for operating mechanism over-travel, provides rotational freedom allowing the contacts to mate squarely and assists the main breaker spring during the initial acceleration phase of the opening cycle. The latter of these builds up operating mechanism velocity which provides the impact opening force when the caged spring bottoms.

The third mentioned function allows the contacts to rest squarely against one another when made providing the best electrical and thermal conditions. The contacts will first touch at a point but then rock over to make a "three point" suspension. If this spring were not there and the contacts rigidly operated the single point contact would remain. There is even the possibility that this rocking action could act like arcing contacts and main contacts in conventional circuit breaker design. If so, the first point of contact and last point of break would suffer the greatest erosion--acting as arcing contacts. The other points of contact would then remain in somewhat better condition and act as main current carrying contacts. Furthermore, this rocking action may assist in breaking any contact welding upon opening.

This spring will be made of Inconel "X" as this material will have adequate spring properties at the temperature and time requirements. The Inconel "X" material must have the right heat treatment and low enough stress to have low relaxation for long times at 540°C.[22]

The spring design shown is a two thread square wire spring milled from a tube. This spring offers excellent end terminations and balanced forces (two thread design).

f. Skin Effect - A simple skin effect calculation[24] for the electrodes using a μ of one for the material gives

$$S = \frac{5030}{\sqrt{\frac{\mu f}{\rho}}} = .655 \text{ cm} = .258 \text{ inches}$$

where S = current penetration

μ = magnetic permeability = 1

f = frequency = 2000 cps

and ρ = resistivity for nickel = 34×10^{-6} ohm-cm.

Although nickel is magnetic this will not change the depth of current penetration much from that of a non-magnetic material. This is so because the 600 amp current in a 1" dia. conductor will deeply saturate the material (Ni) reducing its permeability to very nearly 1.0. The portion of the current at the deeper penetration will be small which in turn will not saturate the material. Here there will be a more pronounced skin effect due to the higher permeability which will result in a rather sharp cut-off of the current penetration

Because of this skin effect the center portion of the electrode is useless except as a thermal conductor. Therefore, the center portion is left in, in the fixed electrode of Figure 31, but the moving electrode is hollowed to house the wipe spring. This spring location gives the best point of applied force--close to the contact--for short wheelbase pivot.

g. General Materials - The temperature ($1000^{o}F$-$538^{o}C$), the vacuum (10^{-15} Torr), and the life (20,000 hrs.-2.28 yrs.) are stringent specifications for materials. In general, any material that can survive the first three of the above can survive the radiation environment. Standard materials used in earth bound, room temperature electrical equipment of this type are completely unsatisfactory. Even many materials used for short space life equipment or those used at the lower temperatures--are inadequate for this application.

The ones most useful are, of course, the low vapor pressure metals and ceramics.[25] For this reason all present design thinking has been around these materials.

3. Actuator Mechanisms

a. General - Two approaches are available for actuator mechanisms for these interrupting devices:

- A hermetically sealed chamber, pressurized with inert gas, necessary coils, latches, and other mechanisms of conventional design including bearings with high temperature lubrication.

- An open mechanism, exposed to high vacuum, which avoids bearings by using flexural pivots.

Because of the lack of data on high temperature lubricants for 20,000 hours life in the presence of the reactor leakage radiation and the additional modes of failure possible with hermetic seals protecting the mechanism, more effort has been placed on investigation of non-conventional actuator concepts applicable to the open, flexural pivot approach.

The comparisons and trade-offs between the two approaches are judged to be:

Hermetically Sealed	Open Flexural
Advantages	Advantages
Uses conventional design	No hermetic seals to fail
No vacuum environment to cause welding of bearings or other contacting surfaces	No sliding bearing surfaces or lubricants required
Better heat transfer for coils	
Disadvantages	Disadvantages
No 20,000 hour 550°C lubricants proved	Impact surfaces not proved for durability and welding
Reliability risk at hermetic seal	Poor heat transfer
	Problem of durable, non-welding impact surfaces

Weight trade-off between the two approaches is not yet defined.

b. Hermetically Sealed Mechanisms - This conceptual approach would comprise a completely hermetically sealed actuator mechanism including interruption device or devices. Only electrical power and control loads would enter the hermetic enclosure. The interior would be charged to one half atmosphere of an inert gas such as nitrogen. Relatively conventional linkage mechanism would be used. Springs, lubricants, and other materials used would have to meet the high temperature nuclear radiation environment. No data is presently available to support selection of a lubricant which would be sure to enable operation for 20,000 hours in this environment. Failure of the hermetic seal would introduce additional modes of failure because of the addition of the vacuum environment.

Failure of the seals on the vacuum interrupting device inside the hermetic enclosure would lead to failure of interruption capability because of high gas pressure. This failure mode could be obviated by sealing only the contacting mechanism inside the hermetic chamber and mechanically coupling to the interrupting device through bellows. This adds more modes of hermetic seal failure for the mechanism and converts the seal failure mode for the interrupter from one of interruption capability to possible contact welding in the higher vacuum. Based on the lack of 20,000 hour lubricant life data in the required environment and the need for hermetic seals the open flexural approach was selected.

c. Open Flexural Mechanism - Figure 32 shows an open flexural actuator mechanism. The philosophy applied was to avoid the use of bearings (ball or sleeve), sliding surfaces, lubricants (dry or otherwise), and have a minimum of contacting surfaces, utilizing anti-weld materials in these. Where motion is required, springs and flexures are to be used.

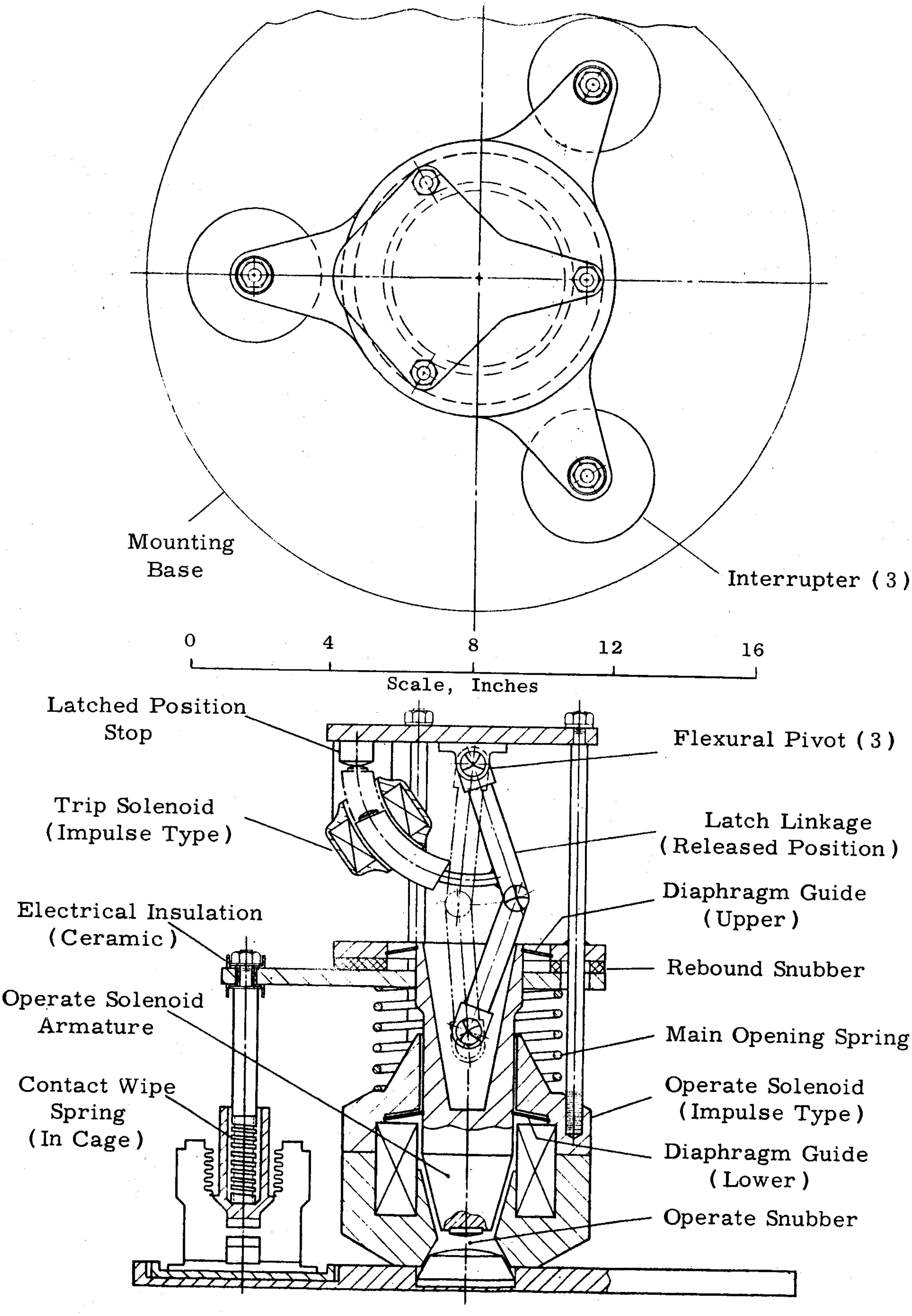


Figure 32. Open Flexural Actuator Mechanism - AC Circuit Breaker.

This design has been started around a solenoid drive-mechanical latch-solenoid trip mechanism having the following specifications -

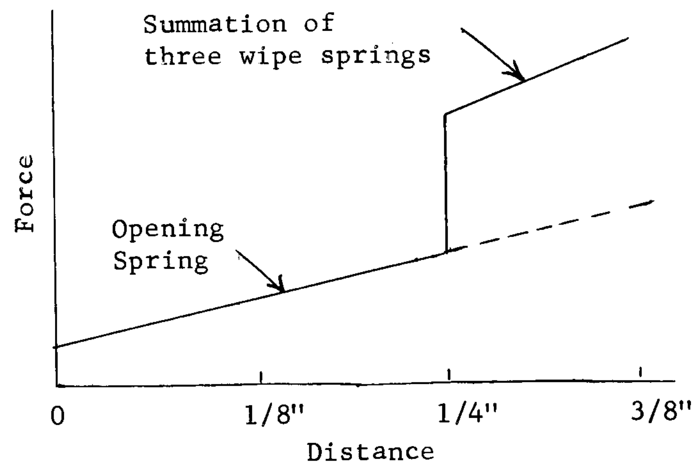
Contact gap: 1/4 inch

Over-travel of wipe spring: 1/8 inch

Contact load: 50 lbs. per pole

Speed of contact closure: 40 inches/sec. at time of touch

The force/distance diagram is of this general shape -



The operate solenoid is energized only long enough to pull in and latch the mechanism--a fraction of a second. The first 1/4 inch of travel the moving parts are accelerated to about 40 in./sec. velocity and the opening spring is being loaded. At this time, the contacts make and the caged contact wipe springs start compressing for the next 1/8 inch of travel. By this time, the linkage has straightened out and the flexural pivots (springs in themselves) nudge the linkage overcenter to the left. Also the operate snubber hits. Releasing of the operate solenoid loads the linkage in compression against the latched position stop and moves the trip solenoid armature into its solenoid. The only parts touching now (that later must part) are the vacuum electrical contacts themselves and the latched position stop. The electrical contacts are loaded by the 50 lb. wipe springs.

To trip the circuit breaker, the trip solenoid is impulsed which kicks the linkage overcenter to the right whereupon the opening spring and the contact wipe springs take over to drive the mechanism open. These accelerate the mechanism for 1/8 inch to the point where the wipe springs bottom. The momentum of all of the moving parts provide impact load on the contacts to break the contact welds. The opening spring and left over momentum drive the mechanism the remaining 1/4 inch to the rebound snubber.

d. Breaker Assembly - The three interrupters are mounted on the base plate around the actuating mechanism, Figure 32. These are electrically insulated from the base by beryllium oxide to provide a good thermal path to the heat sink. The moving electrodes are attached to the operating mechanism through ceramic insulators in the main spider. Both these and the solenoid armature are supported or suspended by two spider-like diaphragms. These diaphragms with their long wheelbase allow the armature and main spider to move freely along the axis of the armature but restrain the motion in all other directions including rotational motion. The latch is a two member linkage of the stiff arm overcenter type utilizing flexural pivots at the joints. This design offers a no-sliding-action therefore no-galling latch mechanism. In the open position, the knee freely extends to the right and in the latched position it is restrained against a stop to the left. A small solenoid is used to trip or kick the knee to the right just overcenter, allowing the contact wipe springs and the main spring to drive the linkage, contacts and mechanism to the open position.

Snubbers or stops are required in just four places -

- to snub the main solenoid and mechanism in its closing direction, operate snubber stop Figure 32.
- to snub the main solenoid and mechanism in its opening direction, rebound snubber, Figure 32.
- to stop the linkage in the latched position, latch stop.
- to stop the wipe springs in the cage, tungsten snubber, Figure 31.

The operate and latch snubbers will be the "hammer-against-a-rock" type where the small button is a material like that used in ball mills (Ni-Hard* or similar) and the anvil is a piece of high density-high tungsten.

The rebound snubber presents a different problem. The velocity will be high because there is nothing to reduce the opening momentum except this snubber. The material for this application is an inorganic mat made of mica layers bonded together with an inorganic binder-mica mat. A brief study of this material indicates that it has many properties desirable and required for this application. It does not outgas or sublime in vacuum tube vacuums (10^{-8} Torr) at 400°C, it retains its tensile strength at least for 200 hours at 425°C, its electrical properties are very stable at elevated temperature, and it has resilience like a mat of very dense felt.

The contact wipe spring stop, shown in Figure 31, will be a tungsten ring.

In summation the use of open flexurals that do not need lubrication and do not have moving parts along with the use of tungsten in places where parts come in contact leads to a device that will survive in the high temperature radiation environment.

B. DC ENGINE CONTACTOR

1. Summary

The conceptual design for the 10,000 volt, 10 ampere DC Engine Contactor evolved from the design of the AC Circuit Breaker and the results obtained in the other areas of the project. The material for the contacts, tungsten, was selected for its antiweld properties and interruption capabilities. DC currents of more than twice the rated current were interrupted at 10,000 volts with contact temperatures of 1200°F. The conceptual design is shown in Fig. 34.

2. Vacuum Interrupter

The vacuum interrupter for the DC Engine Contactor is essentially the same as the AC interrupter. The tungsten contacts, however, are only 1/2 inch in diameter which is adequate for the 10 amperes rated current. The contact wipe pressure is 20 pounds which is less than half of the AC interrupter contact pressure. Figure 33 illustrates the interruptor design.

The ceramic-metal vacuum enclosure will be the same for the DC and AC devices. The 10,000 volts will impose a greater voltage stress on the ceramic insulation but the 1 1/2 inches of surface leakage path corresponds to the leakage path of the vacuum capsule used in the interruption tests . In these tests with the contacts parted 1/4 inch, the contacts at 1200°F and the ceramic-metal enclosure at 900°F, the capsule would arc over at 28 KV, over the outside surface in the air. This leakage path in the final design can be increased by ribbing the surfaces. Further protection to the ceramic insulation is provided by the metal shields which were not used in the materials test capsule.

The insulation between the vacuum interrupter and metal mounting base

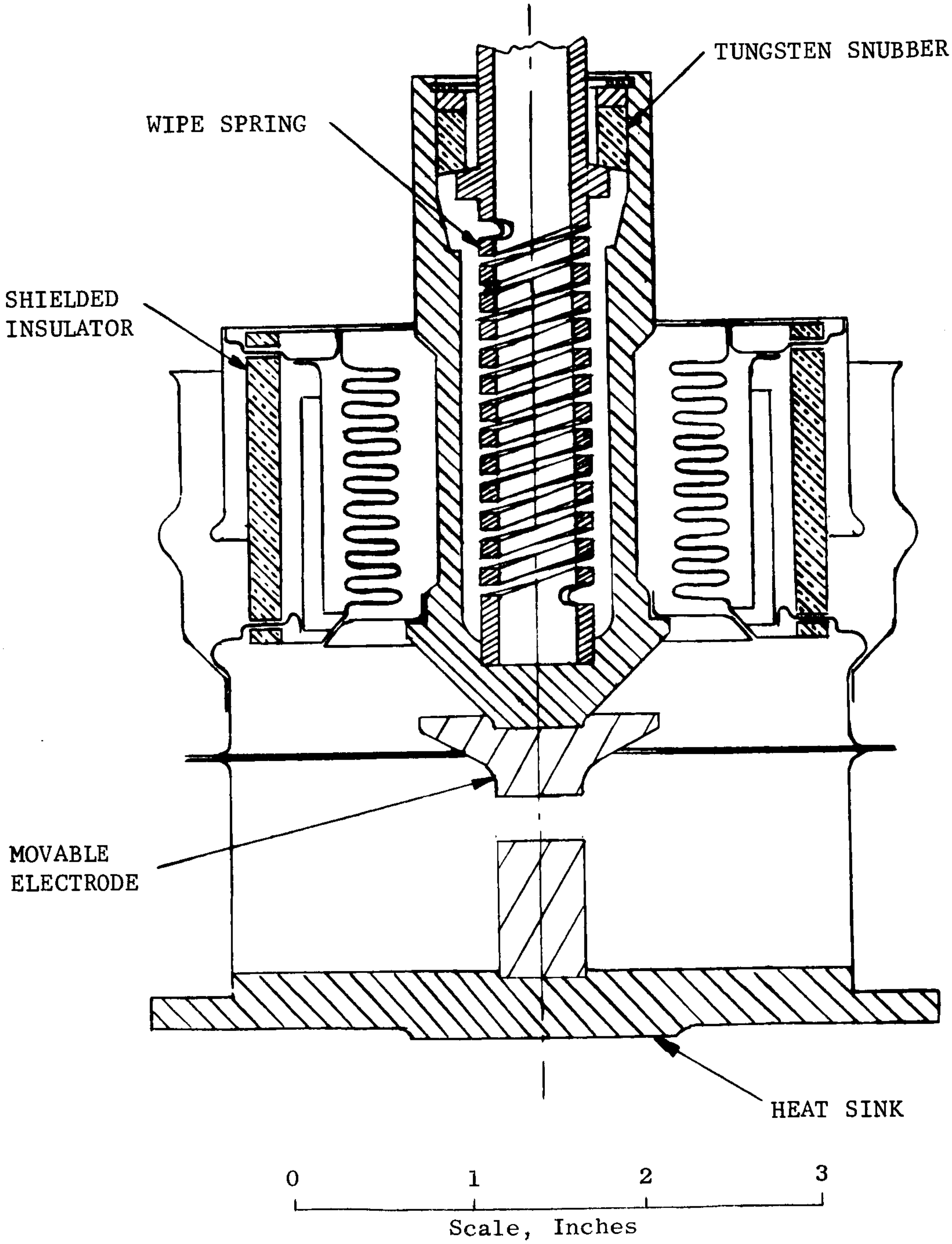


Figure 33. DC Vacuum Interrupter

will be the same thickness as in the AC device. The voltage barrier around the edge of this insulation will be increased in height.

3. DC Actuator

The actuator for the DC Engine Contactor is shown in Figure 34. The flexural design used for the AC Circuit Breaker was adapted to the single pole DC device. In the DC Contactor the vacuum interrupter is mounted coaxially with the actuator mechanism. Since the contact force required is 1/2 that of the AC breaker and the device is single pole, the operating force is 1/6 of the operating force of the 3-phase interrupter. For this reduced force the main operating solenoid is reduced by 1/3 in volume and weight of that required for the AC device. The associated structure is reduced proportionately. The over-all dimensions are approximately 21" long by 7 1/2" square.

The mechanical coupling used to connect the actuator to movable contact must be electrically insulated. To do this a Hewlett type coupling will be used. This type coupling is two metal yokes intermeshed with each other at 90° rotation. These yokes are held apart by a ceramic member that provides the electrical insulation, thus under a tension load the ceramic insulation is under compression.

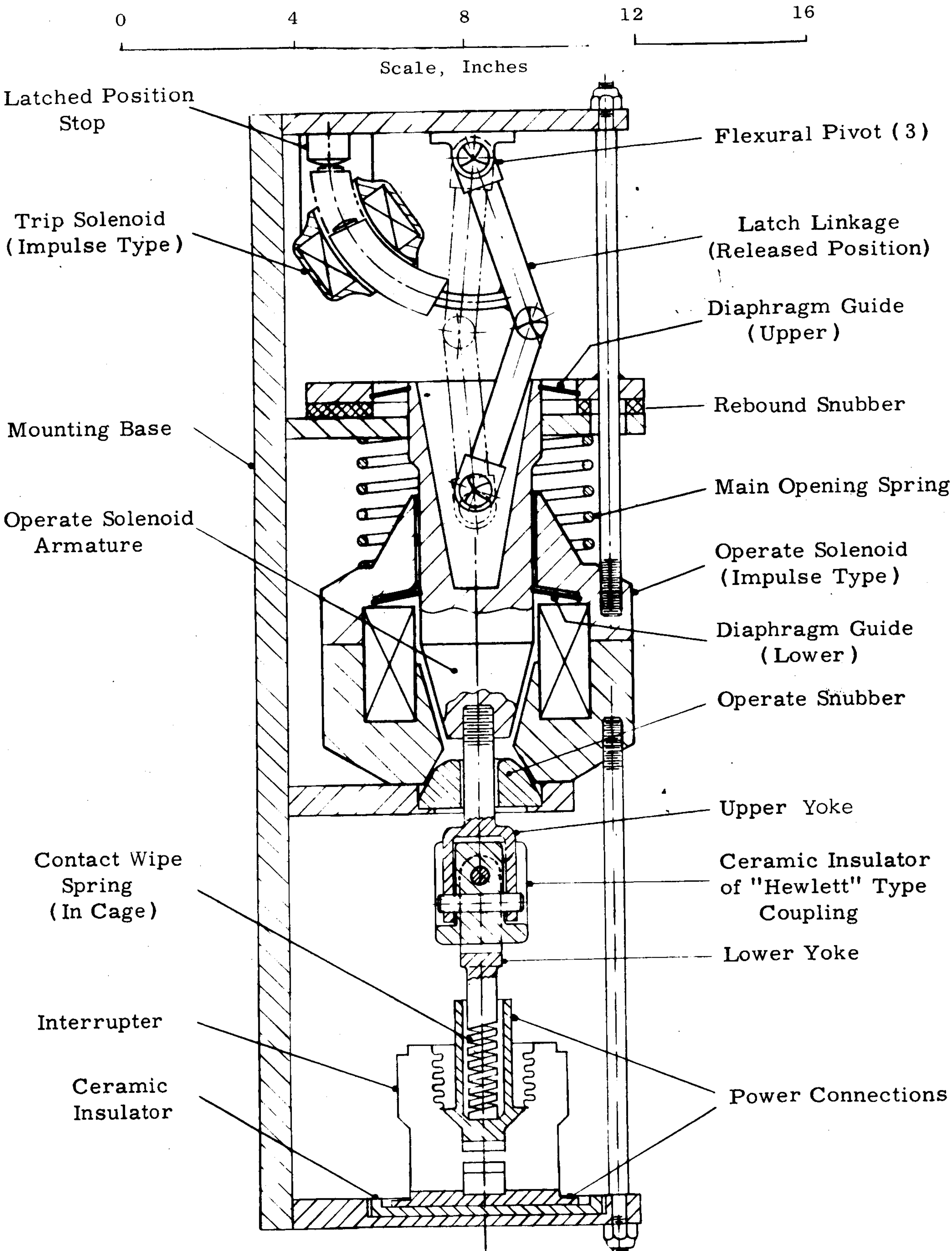


Figure 34. Open Flexural Actuator Mechanism - Single Pole DC Model.

C. Main DC Breaker

1. Summary

The effort on the Main DC Breaker was carried to the point of a conceptual design only. The 10,000 amperes at 100 volts of the specifications for this device narrowed the selection to a hydrogen pressurized interrupter. This selection is discussed in detail under Radiation Exposure in Section II-A.1.

The fundamental design requirements for the device are:

- Electrode diameter 4 to 5 inches
- High pressure hydrogen surrounding contacts
- Contact separation 1/4 inch
- One to four hundred pound operating force
- Free travel impact opening 1/8 inch
- Speed of travel 40 inches/second

Commercial design criteria to be followed are:

- Current transfer takes place at discrete spots or lines
- Mechanics of design should locate the contact spots
- Not more than 25,000 amperes per contact spot
- Contact pressure is as important as contact area

Since this interrupter and actuator must operate at the same heat sink temperature as the vacuum devices, 1000°F, the flexural type actuator designed for the vacuum interrupters will be utilized. The actuator and contact mechanism are enclosed in a gas tight enclosure filled with hydrogen pressurized to 4 atmospheres. Figure 35 is an artist's conceptual drawing of the concept interrupter with a pneumatically operated actuator.

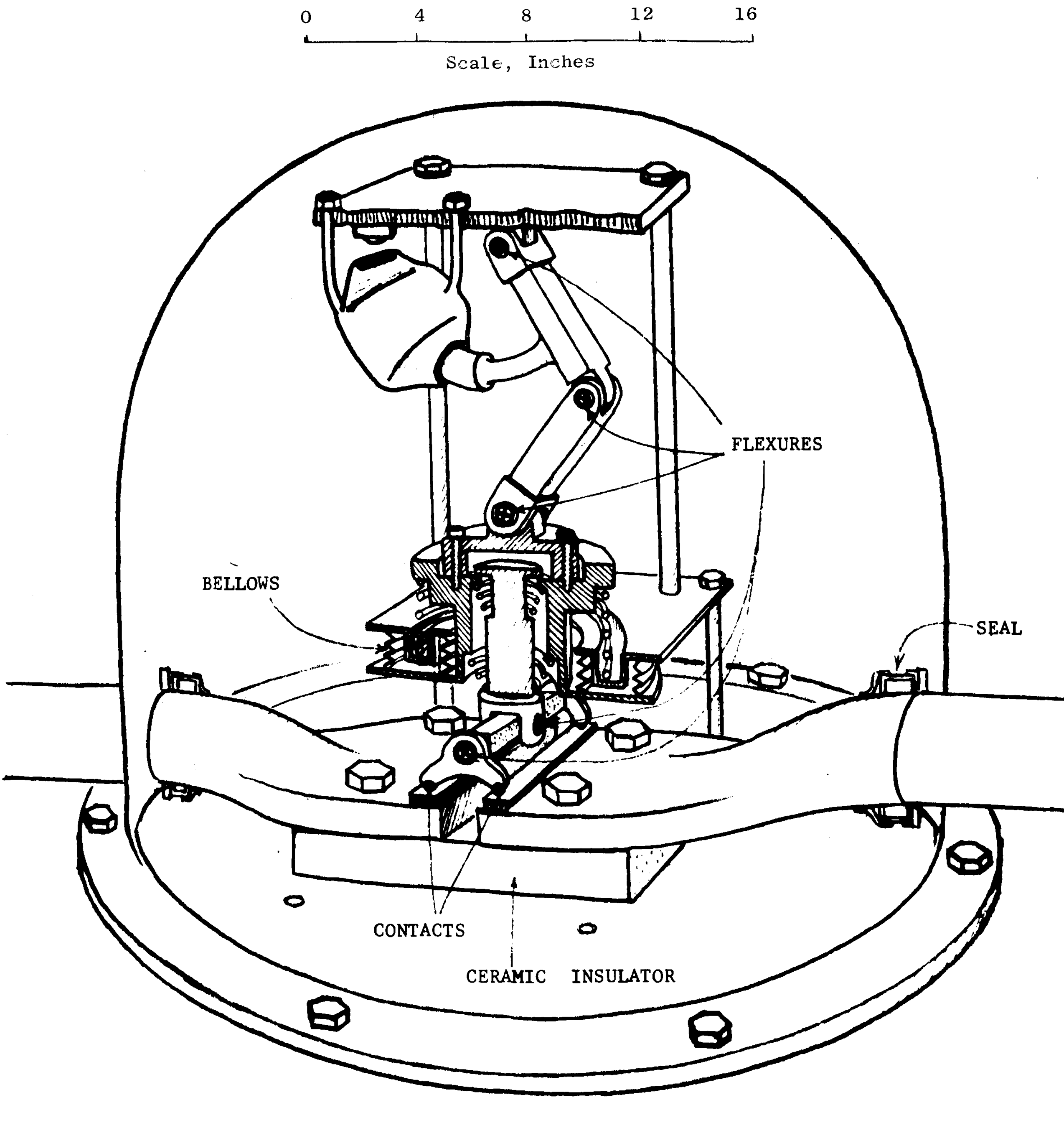


Figure 35. Main DC Circuit Breaker Concept

The actuator takes advantage of the following:

- the breaker contacts must be in a hydrogen environment.
- the breaker must be able to trip quickly at an instant's notice, however, need not be reclosed for a number of seconds or a few minutes.
- a small solenoid operating for a relatively long time (seconds or minutes) can build up the required energy to operate a few hundreds of pounds mechanism pneumatically.
- the above requires only a relatively low level electrical source and associated light duty source switching, wires, etc.
- small high temperature solenoids are easier to design and build than large ones.
- for a given force and distance, the pneumatic system is lighter weight than a direct acting solenoid.

The pneumatically operated actuator makes use of the hydrogen gas essential for interruption of the 10,000 amperes. It replaces the magnetic solenoid that would necessarily be large and require high current to produce the closing force of 400 pounds.

2. Pneumatic Actuator

Figure 36 shows an electro-pneumatic schematic. Basically, a solenoid driven pneumatic compressor compresses H_2 gas to load the tank. This action is started whenever the breaker is open and an external switch is closed. It is stopped by the pressure switch when sufficient pressure is built up.

This stored pressure is released to the actuating bellows piston by the solenoid valve. This can be done only when the breaker is open, neither the internal nor the external trip are in process, and the external CLOSE switch

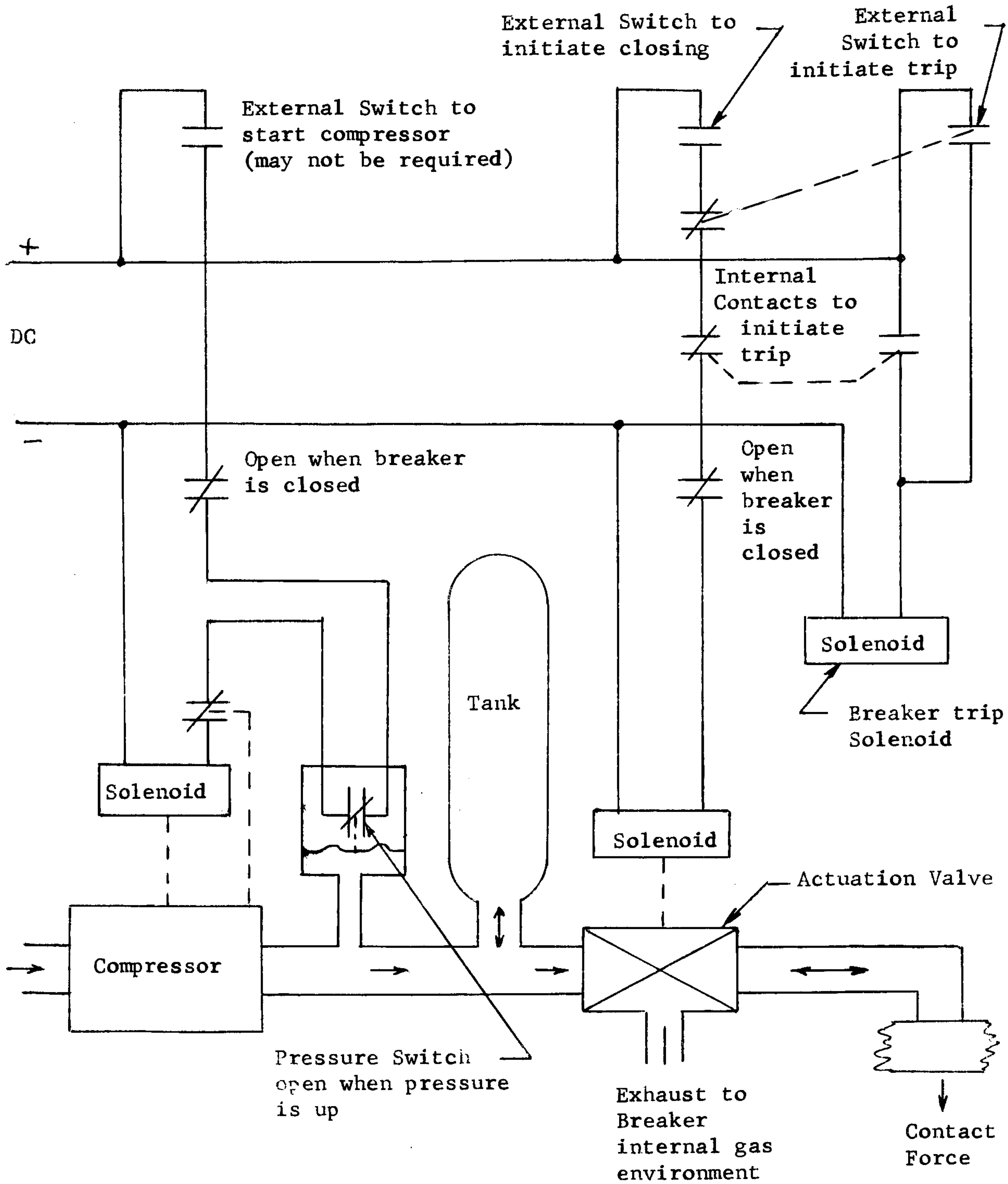


Figure 36. Electro-Pneumatic Schematic

is closed. The release of this pressure to the bellows piston forces the contacts closed and allows the flexure arms to latch holding the contacts closed by mechanical means. The closed breaker opens the solenoid valve which vents the bellows piston to the internal atmosphere of the breaker enclosure. This is done so that the breaker is "ready to trip" and the bellows piston will not hold the contacts closed, or even impede more than minutely, the spring forces that provide the trip action. The mechanical trip action is solenoid instigated the same as it is in the AC Breaker. This is proposed instead of holding the pressure in the bellows piston and releasing it for "trip" because the pressure would vary with temperature and the loss of pressure due to a valve leak would open the breaker.

All of the parts of the valves must be high temperature metals that will not weld such as molybdenum or tungsten.

3. Compressor

Figure 37 shows a conceptual vibrating diaphragm compressor. Such a compressor should work satisfactorily and reliably in the hot dry H_2 environment. The action is nearly self explanatory. The solenoid current can be either AC or DC at any nominal voltage. DC is likely more readily available and is the supply considered in this conceptual compressor. The power is connected through a normally open reed type switch to the solenoid coil. The switch is actuated--closed--by the small permanent magnet mounted on the solenoid armature. When power is applied to the circuit the solenoid pulls the armature up compressing the three return springs, rarefying the gas in the bellows, moving the magnet away from the reed switch. Rarefying the gas causes the inlet valve to open admitting more gas to the bellows. Moving the magnet away from the switch interrupts the solenoid circuit. The return springs

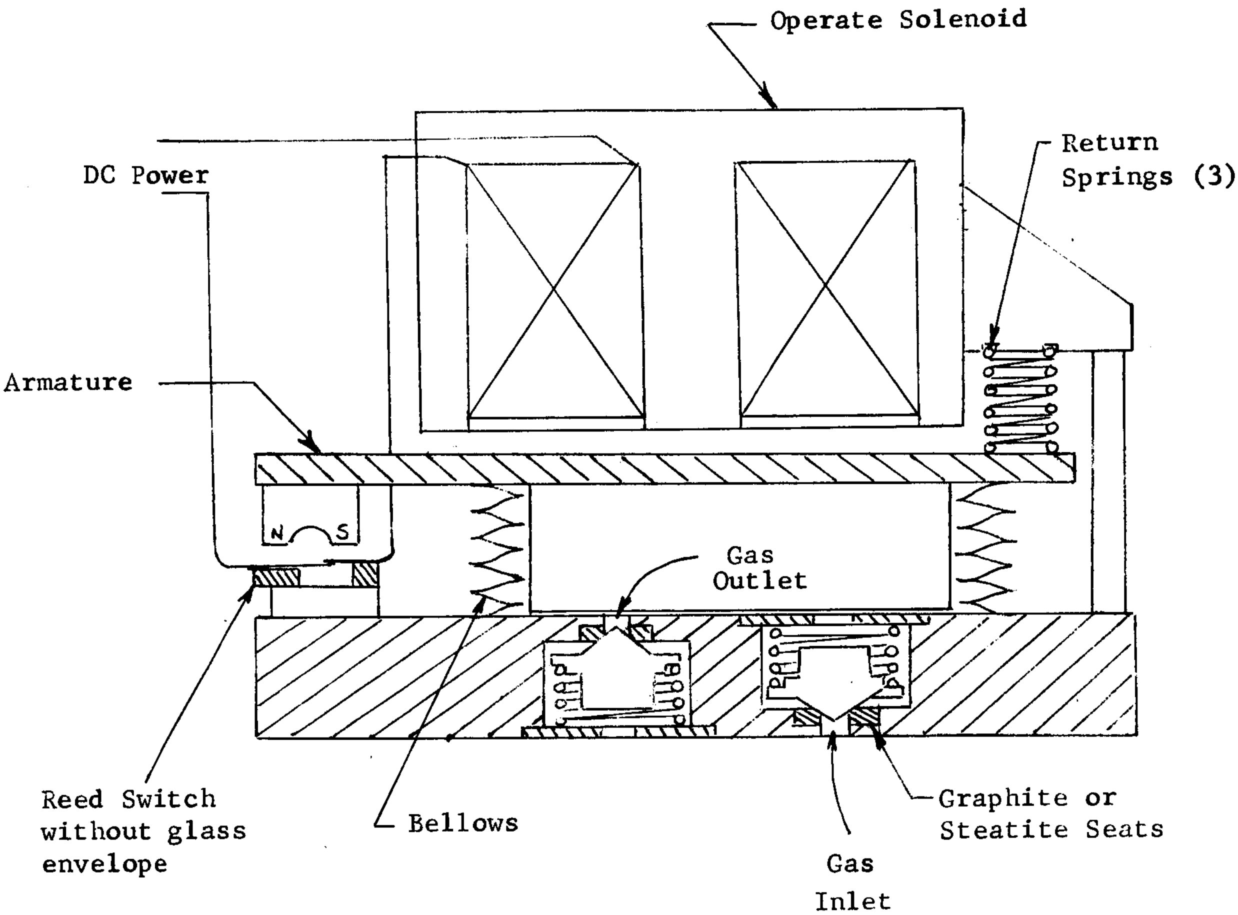


Figure 37. Compressor

push the armature away from the solenoid which compresses the gas in the bellows and forces it out through the outlet valve to the tank. Also this moves the magnet back near the reed switch which recloses the circuit. The action then repeats as often as necessary to build up pressure in the tank. Allowing one to five minutes to compress a hundred cubic inches of hydrogen to a pressure of 20 psi the compressor will be small and light weight.

The bellows piston as shown in Figure 35 has about 16 square inches of area so that 20 psi differential pressure would produce over 300 lbs of force. The compressor would need to provide this pressure or a little greater to the tank. The fact that the surrounding environment H_2 gas pressure varies with temperature, influences the compressor efficiency only as a second order effect. It still requires the same differential pressure to close the breaker.

In the design of this compressor, every effort will be made to raise the compression ratio to improve the efficiency. This must be done, however, without risking the touching or rubbing of the moving parts. Hot, dry H_2 gas is not a good lubricant and sliding motion would cause severe wear or galling. The valve seats will be made of high temperature, wear resisting materials. Stellit seats with tungsten valves should be satisfactory.

The reed switch need not have the usual glass envelope containing hydrogen, since the device will be in the hydrogen atmosphere as would be all other breaker associated internal switches.

4. Solenoid Valve

Figure 38 shows a conceptual three-way solenoid pilot operated pneumatic valve suitable for operation in hot, dry H_2 gas. The same basic philosophy has been used in this conception as in the previous ones, i.e. no

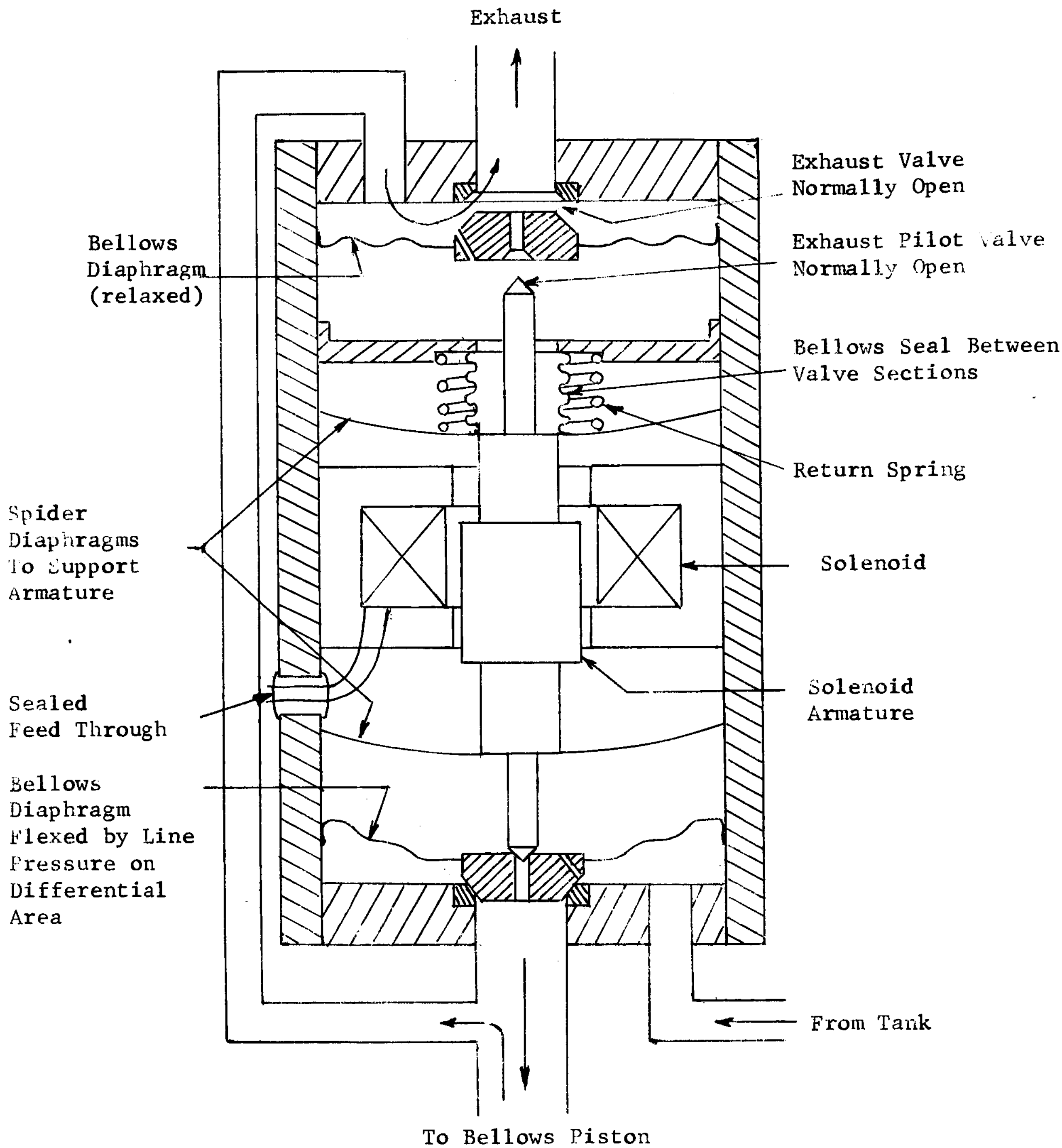


Figure 38. Solenoid Valve

sliding motion of touching parts.

The solenoid armature is suspended on two spider diaphragm guides allowing free movement along the axis of the solenoid while restraining motion in all other directions. This armature has two pilot needle valves, one on each end. One is open when the other is closed. Associated with each of these pilot valves is a diaphragm suspended main valve. The operation of this type valve is based on two principles--

- Reduced pressure in the venturi region of the main valve results in a dynamic force in the direction to close the valve
- Equal pressure on both sides of a diaphragm having unequal areas results in a net static force in the direction to hold the valve closed.

The main valves are closed by the first of the above and are held closed by the second.

When the solenoid is energized, gas can flow from the tank to the bellows piston. A small amount will flow out the upper (exhaust) main valve to establish the venturi reduced pressure region to close this valve. Thereafter the bellows piston pressure will build up to tank pressure.

Releasing the solenoid has the opposite effect. Closing the bottom pilot valve does not immediately actuate the bottom main valve because the pressures and areas are all equal surrounding this main valve. This exists until the bellows piston pressure starts to drop by flow out through the now open exhaust main. Flow from the tank causes reduced pressure venturi action closing the supply main valve.

Careful analysis shows that the relaxed position of the supply valve bellows diaphragm should be with the valve closed while that of the exhaust valve is open.

5. Actuator

The actuator mechanism incorporates the same principles as the open flexured actuator mechanism of the AC Circuit Breaker and DC Engine Contactor. That is, no sliding or rotating surfaces are touching that will weld or gall in the high temperature environment over the long operating life. There will be less tendency to weld in this device because of the presence of the gas than there is in the vacuum of the open type. Lubricants cannot be used in the dry hydrogen atmosphere in the contact area.

The moving parts are shown held in place by the bellows and by conical springs. Movement at right angle to the axis of the member carrying the moveable contacts need to be constricted only enough to prevent parts other than the contacts from touching. For this reason the conical springs were chosen to both center it and provide the wipe spring force. As shown, the bottom end of the flexure pivoted latch mechanism is centered only by the bellows. An alternative would be to add a spider diaphragm.

6. Contact Configuration

Since the electrodes must carry 10,000 amperes and cannot be an excellent electrical conductor like copper, they become very large. For this reason it is not feasible to combine the mechanical mount for the contacts with the gas seal. The large nickel contacts are shown bolted to the bottom mounting plate through a heat conducting insulating ceramic like boron nitride. The ceramic is loaded in compression only. This serves as the main heat sink for the contact losses. The excellent thermal properties of hydrogen gas conducts the heat from other parts to the heat sink. The 4 inch diameter electrodes (800 amps/sq. in.) are sealed upon leaving the enclosure by a round ceramic-to-metal seal. This design yields the least seal length for a given cross section area and are easier to manufacture than other configurations. The electrodes would likely be forged from round stock.

Two bridging contacts are shown; four may be desirable. The design can incorporate any number. Each must be flexure mounted to provide for alignment of each contact member, as shown in Figure 35.

The magnetic force tending to open the contacts, if they are bridged as shown, is about 2 lbs for 10,000 amperes. This is not a very large force, however, this force varies as the square of the current and should surges or overloads increase the current, possibly ten fold, then the force is very significant, being about 200 lbs. Should such overloads exist an alternate contact design can be used to minimize or partially balance the magnetic forces. The extreme of this design can actually result in a force holding the contacts closed. Further information on the actual use of the Main DC Contactor and the load currents during operation will require further effort in this design area.

The tubulation or means for pumping to a hard vacuum and baking to remove all traces of oxygen is not shown in sketch. This same tubulation would be used to pressurize with hydrogen.

7. Conclusions

Listed here are some of the advantages and disadvantages of the electro-pneumatic actuator for the Main Breaker.

a. Advantages:

- Light weight potential.
- Low electrical demand for operation.
- Light duty external control switching.
- Easily capable of increased contact force should it be necessary.
- A modified version could control the gas pressure in the contact region over the temperature range if desirable.

b. Disadvantages:

- More complex than direct solenoid.
- More time involved between reclosings.

V. PROTOTYPE SWITCHGEAR DEVELOPMENT PLANS

The results of the fundamental reviews, investigations and experimental testing in Phase I have been used to synthesize a development program which will lead to the construction and test of demonstration units of the Main AC Circuit Breaker and the DC Engine Contactor. This program is now being carried out under NASA Contract NAS 3-6467. Detailed program plans may be reviewed in the documents of this program.

The initial period of the prototype development program will involve design and fabrication of suitable vacuum switch elements and actuators for the switchgear devices identified above. The necessary vacuum technology to insure long term high vacuum operation inside the switch at its high operating temperature will be carried out in this period. The second period will involve the assembly and check-out of the devices and extensive test evaluation.

The initial testing will insure the mechanical qualification of the devices to withstand stresses similar to those in the Saturn 1B launch. These include shock, vibration, acoustic noise and acceleration. After heat runs and a 1,000 hour vacuum endurance test on the finished switchgear, a series of electrical interruption tests will be carried out to evaluate their durability and performance characteristics.

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VII. APPENDIX A - RADIATION EFFECTS STUDY

I. Introduction and Statement of Work

This report presents the initial evaluation of nuclear radiation effects on materials and gases contained in electrical switchgear applicable to space nuclear power systems. The work was performed as part of the Phase I studies in support of the General Electric - Space Power and Propulsion Section Contract NAS 3-2546 with NASA for the Development of High Temperature Radiation Tolerant Switchgear for Space Nuclear Electrical Systems.

This effort was directed toward conducting a preliminary study and literature review of the effects of radiation on the materials and gases that have potential application in switchgear under combined environments of temperature and radiation at both reduced and high pressures. The primary purpose was to define the immediate and specific problem areas resulting from the combined environment.

The criteria that were used as the basis of this evaluation are presented in Table I. A sketch of a model type switchgear for the configuration three electrical switchgear devices specified by GEATL/NASA is shown in Figure I. Two modifications are noted to the original environmental criteria specified by NASA.

The total nuclear radiation dosage of 10^{15} neutrons/cm^2 and 10^9 rads gamma obtained in 20,000 hours were maintained as criteria for this study. This denotes radiation rates of 5×10^{10} neutrons/cm^2/hour and 5×10^4 rads/hour of gamma. For this investigation, the dose rates were increased by a factor of 10 to 5×10^{11} neutrons/cm^2/hour and 5×10^5 rads/hour of gamma.

The temperature of 1000^{o}F is specified as the heat sink temperature. As a reasonable estimate, 1300^{o}F was used as the maximum material temperature as a basis for this study.

Statement of Work

Dose Rate Effects - Perform calculations to determine expected maximum ionization rates on representative models of the switchgear designs resulting from nuclear radiation in the temperature-pressure environment.

Investigate possibility of gas liberation from the component parts within the switching device.

Calculate gamma heating in the various materials contained in the switchgear.

Total Dosage Effects - Conduct a literature review of the effects of radiation on materials used in switchgear to include topics of:

Change in physical properties of materials

Effect of radiation on magnetic materials

Effect of radiation on integrity of pressure seals, high and low pressure, active and metallized types.

Sublimation of Materials - To determine possible additional detrimental effects to materials in high temperature - low pressure applications; sublimation rates of the materials in the switchgear were calculated. Evaporation of materials inside the switchgear may prove detrimental to long term missions and affect the integrity of seals, electrical contact surfaces and increase ionization in the device.

TABLE I

Preliminary Specifications: SNES Switchgear

	AC BREAKER 600 A 1000 V 2000 cps	DC CONTACTOR 10 A 10 KV	DC BREAKER 10 KA 100 V
ENVIRONMENT			
Radiation Rate*			
Gamma, rads/hr.	5×10^5	5×10^5	5×10^5
Neutrons, $n/cm^2/hr$.	5×10^{11}	5×10^{11}	5×10^{11}
*Rates noted are factor 10 > than specified by customer			
Pressure			
Air, mm HG	$10^{-4}-10^{-9}$	$10^{-4}-10^{-9}$	
Gases, Nitrogen, psi	$10^{-4}-10^{-9}$ mm Hg	$10^{-4}-10^{-9}$ mm Hg	7.4-29.4
Hydrogen			74 - 300
Sulfur Hexa-fluoride, psi	—	—	74 - 147
Temperature, $^{\circ}F$	RT-1300°F	RT-1300°F	RT-1300°F
Total Dosage (Acquired in 20,000 hours) Gamma, Rads; Neutrons, n/cm^2	10^9; 10^{15}	10^9; 10^{15}	10^9; 10^{15}
SWITCHGEAR DEVICES			
Design			
Envelope	Alumina Beryllia	Alumina Beryllia	Alumina Beryllia
Contacts	Wimpreg Cu (TH,TA,imp)	Mo	Cu
Shield	MO,Ni,SS $Cu(O_2$ free)	Mo,Ni,SS $Cu(O_2$ free)	Mo,Ni,SS $Cu(O_2$ free)
Seals High Temp Braze	Au-Ag	Au-Ag	Au-Ag
Active type	Ni,Ti	Ni,Ti	Ni,Ti
Metallized type	Mo/Mn	Mo/Mn	Mo/Mn

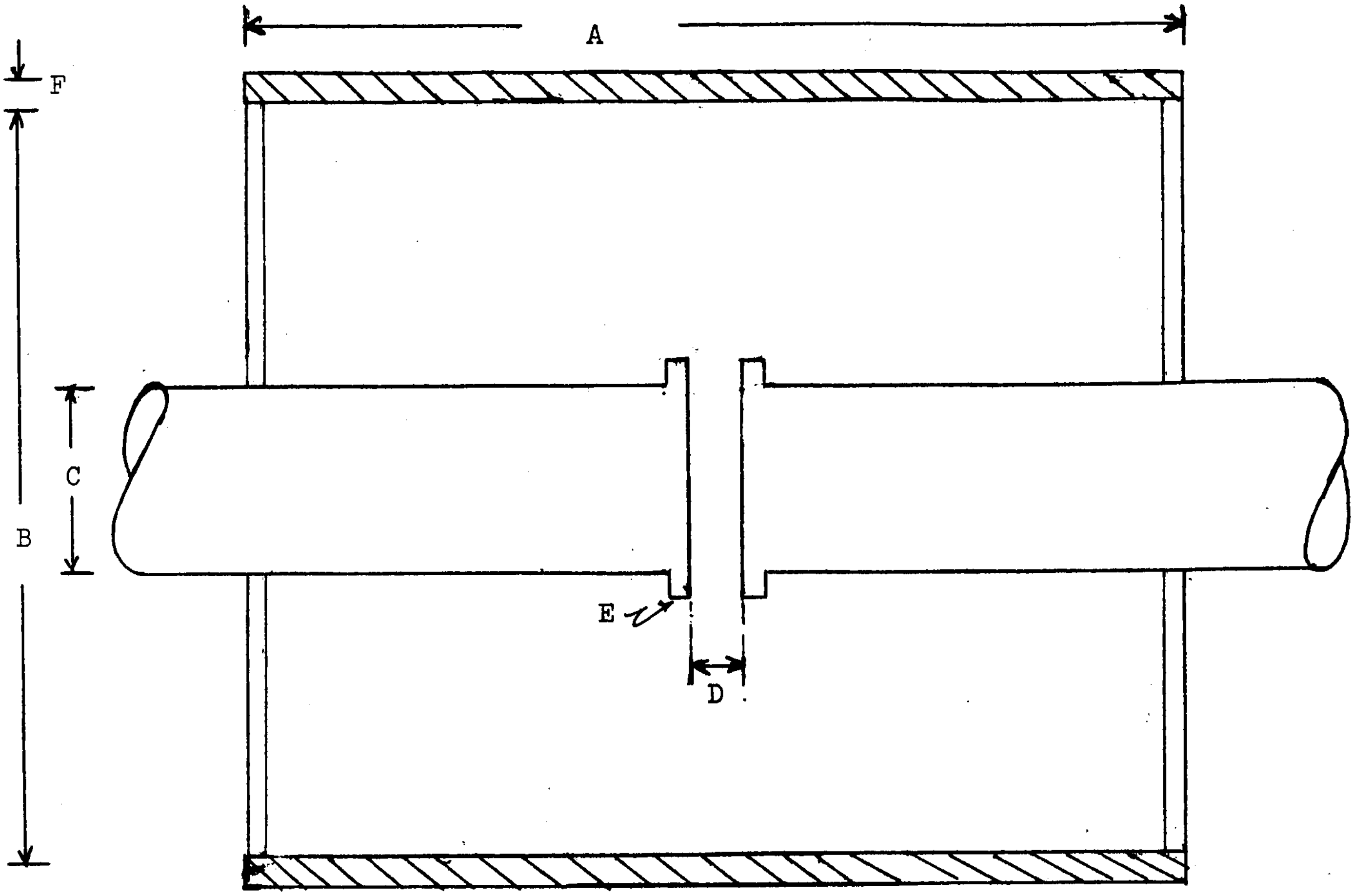

Figure 1

Model Switchgear Configuration Used For Radiation Effects Evaluations

Dimensions	AC Breaker 600A-1000V	DC Contactor 10A-10KV	DC Breaker 10KA - 100V
A	5"	5"	20"
B	4" Dia.	4" Dia.	16" Dia.
C	1" Dia.	1" Dia.	1" Dia.
D	.25-.50"	.25-.50"	.25-.50"
E	1.25" Dia.	1.25" Dia.	1.25" Dia.
F	.125"	.125"	.125"
Volume, cm^3	963	963	6.6×10^4

II. Summary

A summary of the various areas investigated in this study are presented below:

1. Ionization rates were computed for both neutrons and gamma radiation on the various gases at respective ambient conditions of temperature and pressure. The increased ionization due to radiation incident on the outer envelope is included. Computations indicate that electron emission from the outer envelope contributes the highest ionization rate in the switchgear.

2. Limited information is available on gas liberation from materials due to irradiation - essentially all data are presented on a qualitative basis rather than quantitative.

3. Nuclear heating within the various materials in the switchgear appear to present minimum heat addition to the ambient temperature environment of 1000°- 1300°F.

4. Total radiation-dosage of 10^{15} neutrons/cm^2 will present little problem to the structural integrity of materials. Essentially, threshold levels for detecting initial structural defects will not be reached.

5. In some magnetic materials, threshold changes are reached at 10^{15} neutrons/cm^2 total radiation dosage. However, the majority of magnetic materials do not exhibit nuclear effects in their physical properties before 10^{16}-10^{17} neutrons/cm^2. Hard alloy type magnetic materials are the more radiation resistant.

6. Seal integrity is difficult to ascertain due to the long mission requirements of 20,000 hours together with ambient effects of pressure and elevated temperature. Utilizition of active type seals would provide increased stability in the combined radiation-temperature-pressure environment than the metallized types.

7. Sublimation of materials is primarily a temperature-vacuum effect rather than radiation. Loss of materials may result in mechanical defects that may limit material integrity for specific applications. Increased ionization due to radiation incident on vaporized material will occur, the extent of which has not been evaluated.

III. Effects of Radiation Dose Rate

1. Ionization

A. Ionization in the Gas from Radiation

Gamma Rays

Gamma rates are given in rads/hr which is an absorbed dose equal to the deposition of 100 ergs per gram of material. Therefore, 5×10^5 rad/hr. corresponds to the deposition of 1.39×10^4 ergs/gm-sec. The creation of an ion pair in air requires approximately 35 ev, hence the above deposition rate produces where ρ is the density of the material

$$\boxed{2.48 \times 10^{14} \times \rho \qquad \frac{\text{ion pair}}{\text{cm}^3\text{-sec.}}}$$

in gm/cm^3 The ionization rates under the conditions of interest are summarized in Table II.

Neutrons

The ionization in any gas resulting from neutron irradiation may be approximated on the basis of first collision removal, that is, the energy lost by elastic collisions with the nuclei of the gas is taken up completely by the recoil and is available for ionization processes. If the neutron collisions correspond to isotropic scattering in the center of mass systems, then, the fraction of energy transformed to recoils is

$$f = \frac{2A}{(A+1)^2}$$

where A is the mass of the recoiling nucleus. With a unit neutron flux the mass density of energy absorption is

$$\boxed{F(e) = 1.6 \times 10^{-6} E \sum_i f_i \sigma_i n_i \quad \frac{\text{ergs}}{\text{gm}} \Big/ \frac{\text{n}}{\text{cm}^2}}$$

where E is the neutron energy in Mev (assumed as 1.0 Mev avg.) σ_i is the nuclear cross section, and n_i is the number of atoms/gm of the i-th constituent of the material forming the gas.

The calculated ionization rates for the gases of interest here are presented; a value of 35 ev/ion pair was used for air, hydrogen, and nitrogen, while 30 ev per ion pair was assumed for sulfur hexafluoride.

Air	--------2.7 X 10^8 ion pairs/gm-sec.
Hydrogen	--------3.57 X 10^{10} ion pairs/gm-sec.
Nitrogen	--------4.32 X 10^8 ion pairs/gm-sec.
Sulfur Hexa-fluoride	--------1.365 X 10^8 ion pairs/gm-sec.

The resulting ionization rates for the switchgear conditions under consideration are shown in Table II. It may be seen that ionization rates caused by recoil under neutron irradiation is negligible compared to the gamma ray ionization. The gamma ionization rates at high pressure are very substantial.

TABLE II

GAS IONIZATION IN SWITCHGEAR DUE TO GAMMA AND NEUTRON RADIATION

witchgear	Gas	Pressure (P)	Temp. (T) ^oF	Density @ P and T gm/cm^3	Gamma ionization rate ion pairs/cm^3-sec	Neutron ionization rate ion pairs/cm^2-sec
C Breaker 500A-1000V-000C)	Air	10^{-4} mm Hg	1000	$5.6X10^{-11}$	$1.39X10^4$	$1.51X10^{-2}$
	"	" " "	1300	$4.6X10^{-11}$	$1.14X10^4$	$1.24X10^{-2}$
and	"	10^{-9} " "	1000	$5.6X10^{-16}$	.139	$1.51X10^{-7}$
C Contactor 10A - 10KV)	"	" " "	1300	$4.6X10^{-16}$	.114	$1.24X10^{-7}$
	Hydrogen	10^{-4} mm Hg	1000	$3.9X10^{-12}$	$9.67X10^2$	$1.39X10^{-1}$
	"	" " "	1300	$3.2X10^{-12}$	$7.95X10^2$	$1.14X10^{-1}$
	"	10^{-9} " "	1000	$3.9X10^{-17}$	$9.67X10^{-3}$	$1.39X10^{-6}$
	"	" " "	1300	$3.2X10^{-17}$	$7.95X10^{-3}$	$1.14X10^{-6}$
C Breaker 10KA - 100V)	Nitrogen	7.4 psi	1000	$2.12X10^{-4}$	$5.25X10^{10}$	$9.17X10^4$
	"	" "	1300	$1.78X10^{-4}$	$4.45X10^{10}$	$7.7X10^4$
	"	29.4 "	1000	$8.5X10^{-4}$	$2.10X10^{11}$	$3.67X10^5$
	"	" "	1300	$7.1X10^{-4}$	$1.76X10^{11}$	$3.07X10^5$
	Hydrogen	74.0 psi	1000	$1.53X10^{-4}$	$3.8X10^{10}$	$5.46X10^6$
	"	" "	1300	$1.26X10^{-4}$	$3.1X10^{10}$	$4.5X10^6$
	"	300.0 "	1000	$6.1X10^{-4}$	$1.5X10^{11}$	$2.18X10^7$
	"	" "	1300	$5.1X10^{-4}$	$1.27X10^{11}$	$1.82X10^7$
	Sulfur Hexa-fluoride	74.0 psi	1000	$1.1X10^{-2}$	$2.72X10^{12}$	$1.5X10^6$
	"	" "	1300	$9.0X10^{-3}$	$2.2X10^{12}$	$1.23X10^6$
	"	147.0 "	1000	$2.2X10^{-2}$	$5.5X10^{12}$	$3.01X10^6$
	"	" "	1300	$1.84X10^{-2}$	$4.55X10^{12}$	$2.52X10^6$

B. Ionization Resulting from Interactions with the Envelope

Gamma Rays

Radiation incident upon the envelope will produce free electrons in the same manner as in the gas. The envelope is considerably more dense than any of the gas conditions considered, and, therefore, a greater number of electrons are generated. Some of the electrons produced within the case material will be absorbed before they can leave the case. Only those electrons generated within roughly the last millimeter of the case are available for ejection into the switchgear volume. For photon energies of approximately 1 Mev, virtually all the Compton electrons are ejected within a cone having a half-angle of 60° -- higher photon energies cause more pronounced forward scattering of the electrons.

Assuming that radiation is arriving from a single source, only half the area of the envelope is exposed to the incident radiation flux. Radiation which passes through the switchgear volume and interacts with the other wall need not be considered here as the electrons produced will be ejected away from the volume of gas. Considering that interactions near the edge of the half-cylinder will emit some electrons away from the main volume, we shall assume that 75% of the exposed portion of the case will produce eligible electrons. The volume of active case material from this computation was taken as 33 cm^3.

Using the same equation for ion production presented for the gases, the total number of electrons entering the switchgear volume is:

3.27×10^{16} electrons/sec. for alumina

and

2.46×10^{16} electrons/sec. for beryllia

All the electrons so generated have sufficient energy to pass completely through any of the gases contained within the case.

Neutrons

Applying the equivalent reasoning for incident neutrons at 1 Mev, the range in case material of the elastically scattered recoil nuclei is approximately 0.002 cm, and the effective case volume is 0.81 cm^3. Ignoring the angular distributions of the recoils and assuming predominantly forward scattering, and applying the previously used equation for neutron produced ions, the following total number of ion pairs produced through neutron interactions with the case is obtained:

2.2×10^{10} ion pairs/sec. for alumina

and

2.28×10^{10} ion pairs/sec. for beryllia

2. Gas Liberation

Minimum information is available on the quantity of gas liberated from materials during irradiation. The extent of the available information stems from the study of radiation effects on electron tubes where out-gassing of the internal components may alter their electronic performance. Even in these studies, the data are reported in a qualitative manner rather than quantitative. One worker reported a quantitative increase in gas pressure in a tube housed in a 7720 glass envelope from 10^{-6} mm Hg to 10^{-4} mm Hg after total exposure of 10^{16} neutrons/cm^2.

3. Nuclear Heating

The exposure of materials to a nuclear environment will result in increased temperature. The extent of this temperature increase may pose additional problems of localized hot spots or just overall temperature increase that may impair the integrity of a material in its specified application. Both neutrons and gamma radiation add to the heat addition through the process of radiative capture. However, at the radiation rates established as design criteria for this evaluation, the contribution by neutrons is of an order of magnitude less than that supplied by the absorption of gamma radiation.

To evaluate the amount of heat added to the switchgear components, each material is treated separately since the mass absorption coefficients for gamma attenuation vary for different materials. Evaluating each material allows more accurate information for determining the effect of the increased temperature for various material applications.

The relation for computing the amount of heat absorbed in any given material is given as:

$$E_{abs} = \phi \mu_a \rho K E_\gamma$$

E_{abs} = Energy absorbed, watts/cm^3

ϕ = Gamma flux, mev/cm^2-sec

μa = absorption coefficient for a given material, cm^2/gm

ρ = density of material, gm/cm^3

K = conversion factor 1.6×10^{13} watt-sec/mev

E_γ = energy of incident gamma radiation, assumed as 1.0 Mev

The energy of the incident gamma radiation is assumed to average 1.0 Mev. Utilizing this value, the incident gamma flux is equivalent to $5.5 \times 10^5 \frac{\text{Mev/cm}^2\text{-sec}}{\text{R/hr}}$, which, when applied to a radiation rate of 5×10^5 R/hr gives the total flux of

2.75×10^{11} mev/cm^2-sec incident on the switchgear package.

Table III lists the results of the amount of heat addition in terms of watts/cm^3 to the materials in the switchgear devices. A second column is included also in units of watts/gm. From this Table and knowing the total grams of any one material in the switchgear, a representative value for the total heat may be found.

As an example, the total amount of heat added in two of the largest volumetric parts of the switchgear were computed. Both the outer envelope and the solid electrical lead-in rods of the AC Breaker were used. Using model typical dimensions of 4" ID x 4.25" OD x 5" long for the envelope of Beryllia the total heat added is 0.5 watts; similarly, dimensions of 1" dia x 4" l (2 units) for the solid electrical lead-in rods of stainless steel; the total heat added is 0.45 watts. This total heat addition of approximately 1 watt will be of negligible contribution to the total operational temperature of 1000° - 1300°F.

TABLE III

GAMMA HEATING IN MATERIALS IN SWITCHGEAR DEVICES

Material	GAMMA HEAT ADDITION	
	watts/cm^3	watts/gm
Alumina	4.5×10^{-3}	1.1×10^{-3}
Beryllia	3.2×10^{-3}	1.1×10^{-3}
Aluminum	3.2×10^{-3}	1.2×10^{-3}
Copper	9.4×10^{-3}	1.1×10^{-3}
Molybdenum	2.1×10^{-2}	2.1×10^{-3}
Manganese	7.6×10^{-2}	1.1×10^{-3}
Nickel	1.0×10^{-2}	1.2×10^{-3}
Stainless Steel	9.0×10^{-3}	1.1×10^{-3}
MO/MN(1:1)	9.9×10^{-3}	1.1×10^{-3}
Titanium	3.0×10^{-3}	1.1×10^{-3}
Tungsten	2.4×10^{-2}	1.2×10^{-3}

IV. Effects of Total Radiation Dosage on Materials

The major effect of radiation on inorganic type materials is contributed by fast neutrons. Neutron interaction in these materials encounter less resistance from charge fields (electrons) and displace more atoms which cause greater property changes. The extent of the property changes is proportional to the number of displaced atoms. The number of displacements is proportional to the fast neutron flux and time of exposure as well as temperature. The tendency for displaced atoms to return to their equilibrium positions increases with increasing irradiation temperature. Thus, the higher temperature results in less radiation damage.

Gamma rays interact with electrons and produce ionization. The effects of gamma radiation on inorganic materials are about 1/1000 that caused by an equal exposure to neutrons. Generally, gamma radiation is negligible for the displacement of atoms and is considered to play a minor role in permanent radiation damage.

1. Structural Materials

In the irradiation exposure of inorganic materials, metals and ceramics, volume and density changes would be expected due to the introduction of large number of atomic vacancy sites and interstitial positions. Some workers have calculated the expected change and noted that a volume increase per vacancy-interstitial would amount to 50 percent increase in original volume. Actual density measurements on metal irradiated even at room temperature failed to reveal any significant decrease in density. Reason for this is attributed to the fast annealing that takes place in inorganics by which interstitial atoms recombine in the various vacant lattice sites to effect minimum structural effects at low dosages. This recombination process in enhanced at higher temperature. Of the materials planned for use in the switchgear, essentially no structural effects are known to occur after exposure to 10^{15} neutrons/cm^2, 10^9 rads, gamma at temperatures to 1300°F. In the majority of tests conducted, and out of reactor mechanical tests, a total neutron exposure of 10^{19} neutrons/cm^2, representsthe radiation exposure that significantly affects the properties of inorganic materials. At this dosage, total percent change may vary from 5-50 percent. As little as 2 percent change in these properties have been reported to occur at 10^{18} neutrons/cm^2. At the total dosage of 10^{15} neutrons/cm^2 it will be difficult to ascertain whether threshold values in any normal structural property would have been reached.

2. Magnetic Materials

As with metals, neutrons are the primary damaging particle rather than gamma radiation on magnetic materials. This is due to the ability of neutrons to displace atoms in the material affecting the physical properties by ordering or disordering crystal structure. With magnetic materials both structure sensitive and structure insensitive properties are affected; the structure sensitive properties are subject to the most change. Permeability, coercive force and remanence are structure sensitive properties, whereas saturation induction is a structure insensitive property.

Most workers agree that the changes observed can be related directly to the disordering of atoms brought about by irradiation due to correlations observed between the structure sensitive properties and the radiation environment. One element lacking in the data on magnetic materials is that of an evaluation of increased temperature effects. Essentially all of radiation test data available have been accumulated at a maximum temperature of 70°C. One reference, of work by Dietze, on iron and iron-3% silicon irradiated at 570°F gave results of a lowering of magnetization. This work agreed with that of Hall and Haslam in their irradiation of iron-2% silicon to 10^{18} neutrons/cm^2. In general, however, there seems to be rather insufficient data on time-temperature and combined temperature-radiation effects.

Sery and Gordon have studied the effects of reactor irradiation on several magnetic materials at two neutron dosage levels. The results of their work are summarized in Table IV. All of these irradiations were conducted at normal reactor ambient temperature of approximately 140°F. From this data, the high nickel-iron alloys, which have the highest permeabilities and the lowest coercive force changed the most during irradiation. Their high permeabilities were lowered and their low coercive force were correspondingly raised.

TABLE IV

PERCENT CHANGE IN DC MAGNETIC PROPERTIES IN MAGNETIC ALLOYS

Material	Initial Perme-ability (a)	Maximum Perme-ability	Coercive Force	Remanence	Saturation Induction (b)	Loop Rectangularity
			2.7×10^{18} neutrons/cm^2			
3.5% iron	8	-1	5.7	0.8	0	0.8
or thonol	-31	15	-28	-24	-4	-21
5-79 Mo Permalloy	-93	-93	815	-38	-3.2	-36
2V Permendur	2.7	1.7	-2	-0.6	-0.7	0
16 Alfenol	34	15	-8	7.5	-5	13
Nickel Ferrite	1.2	1.4	-4.6	-4	-1.7	-2.4
2-81 Mo Permalloy	-6.8	-3.7	-	-	0.2	-
			1.0×10^{17} neutrons/cm^2			
4-79 Mo Permalloy	-89	-79	403	-44	-	-44
Mumetal	-65	-38	158	-26	-	-23
48 Nickel-iron	-70	-10	99	-26	-	-26
50 Nickel-iron	-31	15	-28	-24	-	-21
3.5 Silicon-iron	8	-1	6	1	-	1
3 Silicon-iron	18	1	-2	-3	-	-1
3-1 Si-Al-Fe	1	1	-2	2	-	-1
16 Al-Fe	34	15	-8	8	-	13
16 Al-Fe	-4	-4	-2	-	-	-
2V Permendur	3	2	-2	-1	-	0

(a) μ at B = 20 gauss
(b) B for H = 30 oersteds

The properties of the 50 nickel-iron alloys changed markedly but not as much as the higher nickel-iron materials. Silicon irons, aluminum irons and 2V Premendur cores proved to be radiation resistant to the irradiation exposures.

McMillan and Howell irradiated 5-79 Mo permalloy to 6 X 10^{13} neutrons/cm^2 and 7 X 10^6 rads. Observations of the hysteresis loop during irradiation indicated no effects due to irradiation at the maximum exposures. From these data and those of Table IV, the threshold level of irradiation damage lies between 10^{14} - 10^{17} neutrons/cm^2. Since the maximum total dosage anticipated in the 20,000 hour mission is approximately 10^{15} neutrons/cm^2, some change may be anticipated in certain magnetic materials. Extrapolation of these data would tend to indicate minimum effects due to radiation; however, temperature effects information are very limited to note any possible added degradation.

A small amount of data are available on combined temperature-irradiation effects in permanent magnet materials. Sery and Gordon exposed materials such as 3.5% chromium steel, 36% cobolt steel, alnico II, V, and XII, cunico, cunife, silmanal, platinum-cobolt and barium ferrites to 10^{17} neutrons/cm^2 at 200°F within an accuracy of $\pm$ 2% open circuit induction, $\pm$ 3% residual induction and $\pm$ 10% coercive force. These studies showed no effects from the radiation exposure.

Table V is a summary of irradiation studies on similar ferrites by Salkovitz, Schindler and Ansell. The materials were also irradiated to 10^{17} neutrons/cm^2 below 170°F. According to these authors, if a 10% change in any of the noted measured parameters arbitarily is considered to be insignificant, then Sample type II and IV, which are nickel-zinc-manganese ferrites and sample type VI, which is a complex ferrites containing mixtures of oxides of nickel, zinc-manganese, magnesium and copper, may be assumed to be unaffected. All other ferrites showed larger changes.

TABLE V

EFFECT OF IRRADIATION OF MAGNETIC PROPERTIES OF FERRITES

Type	Material	Applied H Max Oersteds	ΔH_c Percent	ΔB_r Percent	$\Delta \frac{B_m}{B_r}$ Percent
			1.0×10^{17} neutrons/cm^2		
XII	NiO-Ferrite	14	-8	-36	25
X	NiO-ZnO-Ferrite	7	22	-9	9
IV	NiO-ZnO-MnO-Ferrite	20	0	5	-3
II	NiO-ZnO-MnO-Ferrite	25	0	7	-3
V	NiO-ZnO-MnO-MgO-Ferrite	14	106	-15	-4
III	NiO-ZnO-MnO-MgO-Ferrite	6	14	-12	6
	NiO-ZnO-MnO-MgO-Ferrite	9	40	-6	6
IX	NiO-ZnO-CuO-Ferrite	3	30	-17	18
	NiO-ZnO-CuO-Ferrite	25	21	-15	20
XIII	MgO-MnO-Ferrite	25	48	-1	1
VIII	MnO-ZnO-Ferrite	5	6	-20	24
VI	NiO-ZnO-MnO-MgO-CuO-Ferrite	2	5	0	2

Alley of Bell Telephone Labs exposed magnetic toroids of manganese-zinc and nickel-zinc ferrites to 6×10^{17} neutrons/cm^2 and 4×10^{8} rads at 140-230^{o}F. The magnetic properties studied included permeability, coercive force, remanence, and loop rectangularity. Neither material showed appreciable changes up to 1.5×10^{17}, but the greater exposure caused a 15% reduction in permeability.

Again the temperature effect during irradiation are the limiting criteria for ascertaining the total change that may be anticipated in magnetic materials. Certainly some of the materials specified in the foregoing data probably would not be chosen for application in the switchgear due to their curie points being lower than the 1000^{o}F criteria. Selection of magnetic material with inherently high curie points with respect to their design application will eliminate potential problems in this respect. With regard to irradiation alone, the total dosage of 10^{15} neutron/cm^2 would not impose a problem where drastic reductions or changes in the properties of magnetic materials would develop.

3. Seal Integrity

Titanium is used extensively in the manufacture of ceramic tubes which have exhibited good stability in a radiation environment greater than 10^{16} neutrons/cm^2. In the utilization of Nickel-Titanium as a seal in the switchgear one important disadvantage is that titanium is a excellent getter of oxygen, nitrogen, and carbon dioxide at high temperature 500°F. If appreciable quantities of these gases either are present in the pressurized switchgear package or become present due to out gassing of internal metal and ceramic materials under irradiation and temperature, oxide and nitrides of titanium will form. A progressing action due to the long time mission requirements may result in etched-type channels through the seal material which would eventually cause a leak or possible rupture of the seal.

However, more detailed investigations both in reviewing literature or actual testing appear warranted to provide a more valid basis on determining the integrity of various seal materials.

The General Electric Tube Department has irradiated 200 TIMM components of which each unit contains five seals of the active nickel-titanium type to fosterite ceramic. In these tests no failures were detected in the seals when irradiated to 3×10^{18} neutrons/cm^2 at 1076°F.

Metallized type seals are used extensively in the manufacture of power tubes. Most common type seal is that of Molydenum-Manganese coatings or deposits on ceramic materials which are then overbrazed with gold or silver or mixtures of the gold-silver which in effect provides the seal. No radiation data has been found that would help lend integrity to these type materials in a nuclear environment. In a verbal communication with A. Hase, General Electric Tube Department, both mechanical and chemical degradation may be expected in use of the Mo-Mn seal design at temperatures in excess of 500°F. The limiting property is the non-linear temperature coefficient of the seal materials. These are the ceramic, Mo-Mn coating and the high temperature braze overcoating.

V Sublimation of Inorganic Materials in Vacuo

Among the various problems associated with the application of switchgear devices in the thermal-vacuum-radiation environment is that of sublimation or evaporation of materials in the vacuum environment. In the three device types considered, only the outermost envelope will be subjected to the total space environment which is of the order of 10^{-6} mm Hg at 200 km (125 miles) and 10^{-12} mm Hg at 6500 km (4000 miles). In addition, internal vacuum pressure ranging between 10^{-4} to 10^{-9} mm Hg is a design criteria for two of the devices; namely, the AC Breaker (1000 V - 600 A) and the DC Contactor (10 KV - 10 A).

The immediate effects concerning the behavior of the materials in the reduced pressure environment would be the integrity of seals to maintain operational pressure requirements and the general integrity of other materials with respect to their individual applications.

Sublimation of the materials specifically in terms of depth of penetration and total weight loss were evaluated. Each of these are important, for example, as in the evaluation of the integrity of the contact surfaces which must withstand long time stability. Here, depth of penetration by evaporation coupled with loss of material would result in pitted surfaces that would tend to increase the contact surface resistance possibly to the point of causing loss of power transmission in the circuit. Also, the resultant increase in the population of sublimed molecules from the surfaces may effect the deionization (recombination) time of the breaker during the mechanical process while the switch is being opened.

The rate at which molecules leave a surface into a vacuum is given by the Langmuir equation:

$$W = \frac{p}{17.14}\sqrt{\frac{M}{T}}$$

W = rate of sublimation, gm/cm^2-sec

p = vapor pressure of material, mm Hg

M = molecular weight, gms

T = temperature, ^{o}K

For the 20,000 hour mission, this equation may be put in the form:

$$W = 4.2 \times 10^6 \, p\sqrt{\frac{M}{T}} \; gm/cm^2$$

Knowing the area of the various component parts of each switchgear device, this equation is easily utilized to determine the total quantity, in grams, released in the vacuum environment.

Similarly, this equation may be put into a form to evaluate the depth of penetration in a material in vacuum:

$$S = 1.85 \times 10^6 \, \frac{p}{\rho}\sqrt{\frac{M}{T}}$$

S = rate of sublimation, cm/year

ρ = density of solid material, gm/cm^3

or for the 20,000 hour mission, this becomes:

$$S = 4.22 \times 10^6 \, \frac{p}{\rho}\sqrt{\frac{M}{T}} \; cm/20{,}000 \text{ hours}$$

The above equations give the maximum rate of sublimation of any material exposed in vacuo which assumes that none of the molecules that leave the surface return to it. In partial vacuum, some of the molecules will collide with the air or gas atmosphere and be scattered back to the surface. The net result in this case will be that the total loss by sublimation will be lower, but never higher. Also, it is noted that the rate of sublimation increases rapidly with temperature because the vapor pressure of the materials increases rapidly with temperature. In the temperature range considered here of 1000° - 1300°F (811° - 978°K), the actual vapor pressures of the inorganic solids are very small.

TableVI presents the results of the evaluation on basis of rate of depth of penetration and rate of weight loss for the 20,000 hour mission. No direct computation as to actual or total weight loss of the materials in the switchgear was done, since actual areas may vary in the final design. The Table does, however, present adequate data on a rate basis applicable to the 20,000 hour mission which may be easily applied to evaluate actual weight losses and depth of penetration in materials during the design phases of this contract.

TABLE VI

SUBLIMATION RATES OF MATERIALS IN SWITCHGEAR DEVICES

Material	Vapor Pressure, mm Hg		Sublimation Rate, S, cm/20,000 hours		Weight Loss, W, due to Sublimation gms/cm^2-20,000 hours	
	1000°F (811°K)	1300°F (978°K)	1000°F (811°K)	1300°F (978°K)	1000°F (811°K)	1300°F (978°K)
Alumina	10^{-11}	10^{-8}	3.7×10^{-6}	3.4×10^{-3}	1.5×10^{-5}	1.3×10^{-2}
Beryllia	10^{-11}	10^{-8}	2.4×10^{-6}	2.3×10^{-3}	7.2×10^{-6}	6.7×10^{-3}
Aluminum	10^{-11}	5×10^{-7}	2.8×10^{-6}	2.6×10^{-2}	7.9×10^{-6}	3.4×10^{-1}
Copper	10^{-11}	10^{-8}	1.3×10^{-6}	1.2×10^{-3}	1.1×10^{-5}	1.1×10^{-2}
Molybdenum	10^{-11}	10^{-11}	1.4×10^{-6}	1.3×10^{-6}	1.4×10^{-5}	1.3×10^{-5}
Manganese	5×10^{-7}	5×10^{-4}	7.5×10^{-2}	6.6	5.4×10^{-1}	49
MO/MN(1:1)	5×10^{-9}	2.5×10^{-6}	1.3×10^{-4}	1.2×10^{-1}	6.4×10^{-3}	2.9
Nickel	10^{-11}	10^{-11}	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-5}	1.0×10^{-5}
Stainless Steel	10^{-11}	10^{-11}	1.3×10^{-6}	1.3×10^{-6}	1.1×10^{-5}	1.0×10^{-5}
Titanium	10^{-11}	10^{-11}	2.2×10^{-6}	2×10^{-6}	1×10^{-5}	9×10^{-6}
Tungsten	10^{-11}	10^{-11}	1.0×10^{-6}	9×10^{-7}	2×10^{-5}	1.8×10^{-5}

Note: Pressures labeled 10^{-11}mm Hg correspond to vapor pressures 10^{-11} mm Hg and sublimation figures are maximum value

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